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THESIS

PRELIMINARY INVESTIGATION OF A
PROPOSED SONOBUOY RANGING SYSTEM

by

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Preliminary Investigation of A
Proposed Sonobuoy Ranging System

by

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ABSTRACT

The ability to locate and determine the position of an ASW sonobuoy is an essential part of airborne anti-submarine operations. Present methods restrict the parent aircraft's operational capability and yield only marginal data. State-of-the-art frequency control makes it possible to range sonobuoys accurately with radio signals. Sonobuoy position can then be determined by combining this range data with other available information. A system is proposed to both free the parent aircraft from present restrictions and to increase the accuracy of the position information.

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I. INTRODUCTION

In airborne anti-submarine warfare, there is a need for a system which can accurately and continuously display the tactical situation to the local commander. The system should give him accurate relative positions of the aircraft, sonobuoys and contacts as they are determined. It should not restrict the aircraft's flight to a given pattern, altitude or speed. It should not require transmission of signals by the aircraft which could be detected by ECM.

The present system used in this situation does not meet all the above requirements. Its limitations are discussed in Section II. A system is proposed here which, it is believed, will meet the requirements listed above within acceptable limits.

The basic concept is very simple. It depends upon the continuous measurement of the slant range from each sonobuoy to the aircraft and the subsequent processing of this and plane navigational information to provide the sonobuoy field pattern. Processing of the data and the solution of the pattern problem is discussed by Cooley.[Ref. 1]

This thesis concerns itself only with the slant range determination. The method proposed requires the measurement of the phase of a stable radio signal, transmitted from the sonobuoy. As the observer moves in the vicinity of the sonobuoy, the phase of the received signal will change. If the phase of the received signal has been determined at some known range, then the present phase of the received signal can be related to the present range. With this method, continuous slant range between sonobuoy and aircraft is known.

Generation of the transmitted signal and measurement of the phase of the received signal are the most important areas of the proposed system. These areas will be discussed in detail.

It is emphasized that the proposed system is only the initial investigation of the concept. The problems in this system will be delineated and various methods of solution described. Verification of these solutions is needed in some cases. It is concluded that the proposed system is feasible.

II. THE PRESENT SYSTEM

The problem of accurately positioning ASW sonobuoys from the parent aircraft is one that must be solved if the aircraft is to be free to operate around the sonobuoy field and still have accurate knowledge of the tactical situation.

The standard ASW sonobuoy is approximately 4.5 inches in diameter and 36 inches in length. When in the water, approximately 2-4 inches of the sonobuoy remain above the surface. The small cross section available for radar illumination makes radar ranging impossible. The use of radar repeaters or transponders in the sonobuoy is unattractive because of the cost involved and the operational consideration of the aircraft being detected by ECM.

Optical ranging of the sonobuoys is impractical and totally dependent on the weather conditions in the area. Personal observations on a typical patrol mission have shown that at an altitude of 500 feet, the sonobuoy's self contained dye marker is very difficult to detect. The usefulness of marking flares and the small lamp on the sonobuoy for location during night operations is also dependent on the weather conditions.

Current operational procedures locate sonobuoys by means of the On-Top Position Indicator. As the name implies, the indication of "on-top" is received as the aircraft passes over the sonobuoy. There can be considerable error in determining when the aircraft is directly "on-top". The magnitude of this error is dependent on the altitude of the aircraft.

It is obvious that this method does not meet the requirements as outlined in the introduction. The aircraft's mobility is restricted by the necessity of "on-topping" a sonobuoy whenever an updated display of the tactical situation is required.

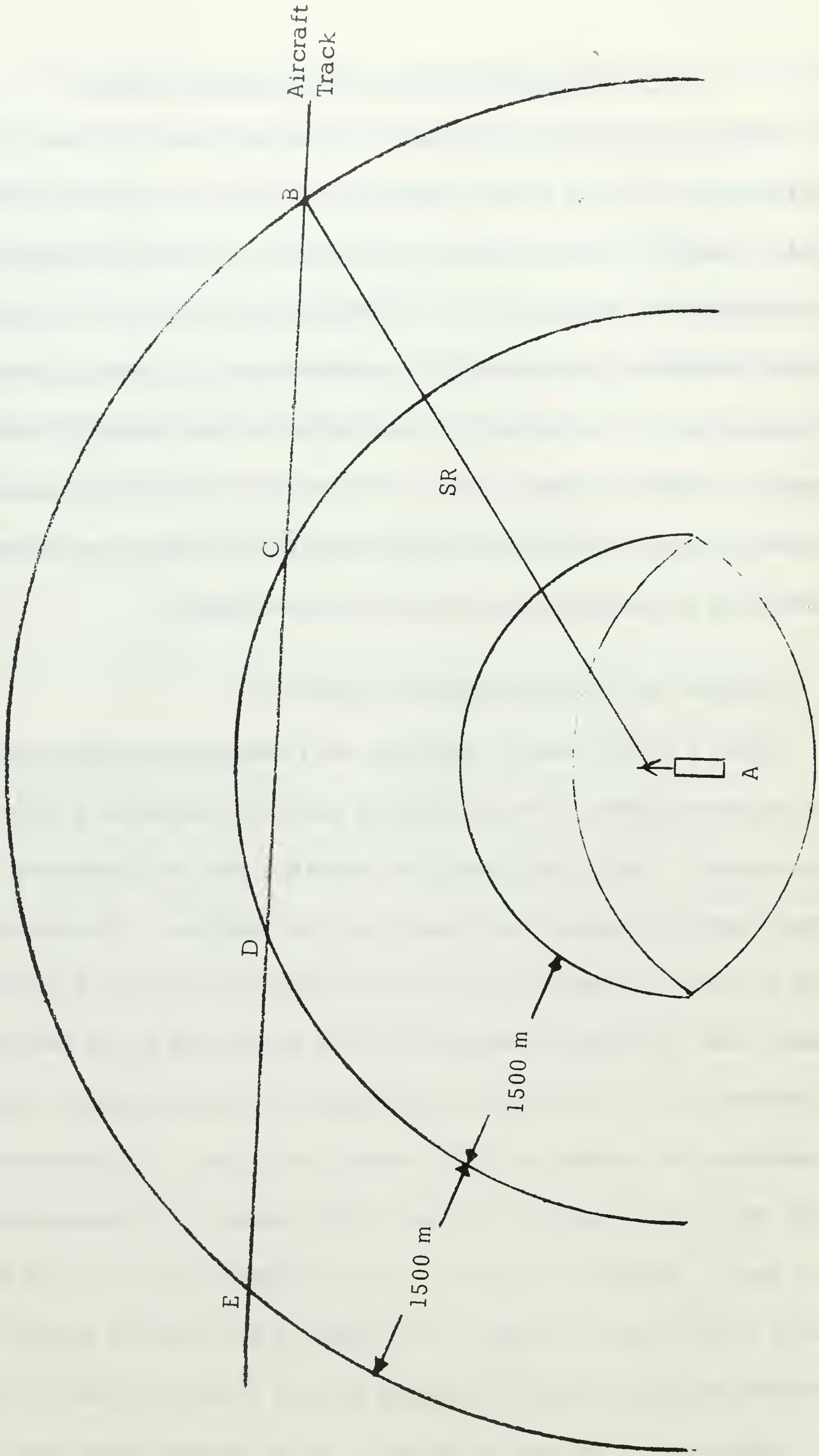
In contrast, the proposed system would in no way restrict the aircraft's movement around the sonobuoy field, and the anticipated accuracy is greater than the present system.

III. THE PROPOSED SONOBUOY RANGING SYSTEM

The basic concept of the proposed sonobuoy ranging system is somewhat similiar in theory to radio navigation systems now in use such as LORAN, OMEGA, and the proposed short-range, precise, navigation system described by Dean.[Ref. 2] All depend on the velocity of propagation of electromagnetic waves. In some systems, position is determined by measuring the time difference between two or more received pulse signals. In other systems such as the system described by Dean and the system proposed here, range is determined by the continuous measurement of the accumulated phase of the received signal.

A. A REVIEW OF THE FUNDAMENTAL CONCEPT

Figure 1 will be used to illustrate the fundamental concept behind the proposed system. The sonobuoy in position A transmits a stable radio signal. The aircraft flying the indicated track will intersect concentric arcs of constant slant range from the sonobuoy. The concentric arcs of constant slant range can also be thought of as arcs of constant phase, with the distance between the arcs determined by the frequency of transmission. For example, the velocity of electromagnetic wave propagation in a vacuum is $3X10^8$ meters per second. At a frequency of $1X10^5$ Hz, one wavelength is equal to 3000 meters or 10 microseconds of time lapse. Referring to Figure 1, as the aircraft continues along the track, it will note an increase in the phase of the received signal of π radians while traveling from point B to point C (or an accumulated time of 5 microseconds between the points). As the aircraft moves from point



The Basic Range Concept

Figure 1

D to point E, it will note a decrease in phase or time of the same amount. While moving from point C to point D, it will note first an increase and then a decrease in the phase.

Thus it can be seen, that if the aircraft has knowledge of the phase of the transmitted signal at the sonobuoy, or the received signal at some known range, it can measure the phase at any other point, and determine the new range as shown. The initial determination of the phase-range relationship could be made before the sonobuoy is dropped from the aircraft, or it could be determined after it is in the water. These alternatives are examined in Section X.

B. THE PROPOSED SYSTEM

The proposed sonobuoy ranging system would include two major modifications to the hardware of the present system. To provide the ranging signal, either a stable crystal controlled oscillator would be placed in the sonobuoy, or the basic carrier frequency would be stabilized. The stability of the oscillator providing the range signal would in effect limit the accuracy of the system. From the previous discussion of the basic concept, it is obvious that once the phase of the signal has been determined at some known range, it must remain constant at that range if the system is to remain accurate.

The second major modification to the present system would be a phase measuring system on-board the aircraft. It is appropriate to point out here that system modifications in the aircraft were not constrained by

cost to the degree that modifications to the sonobuoy were. The on-board equipment would not be expendable, and therefore the cost limitations were much less severe.

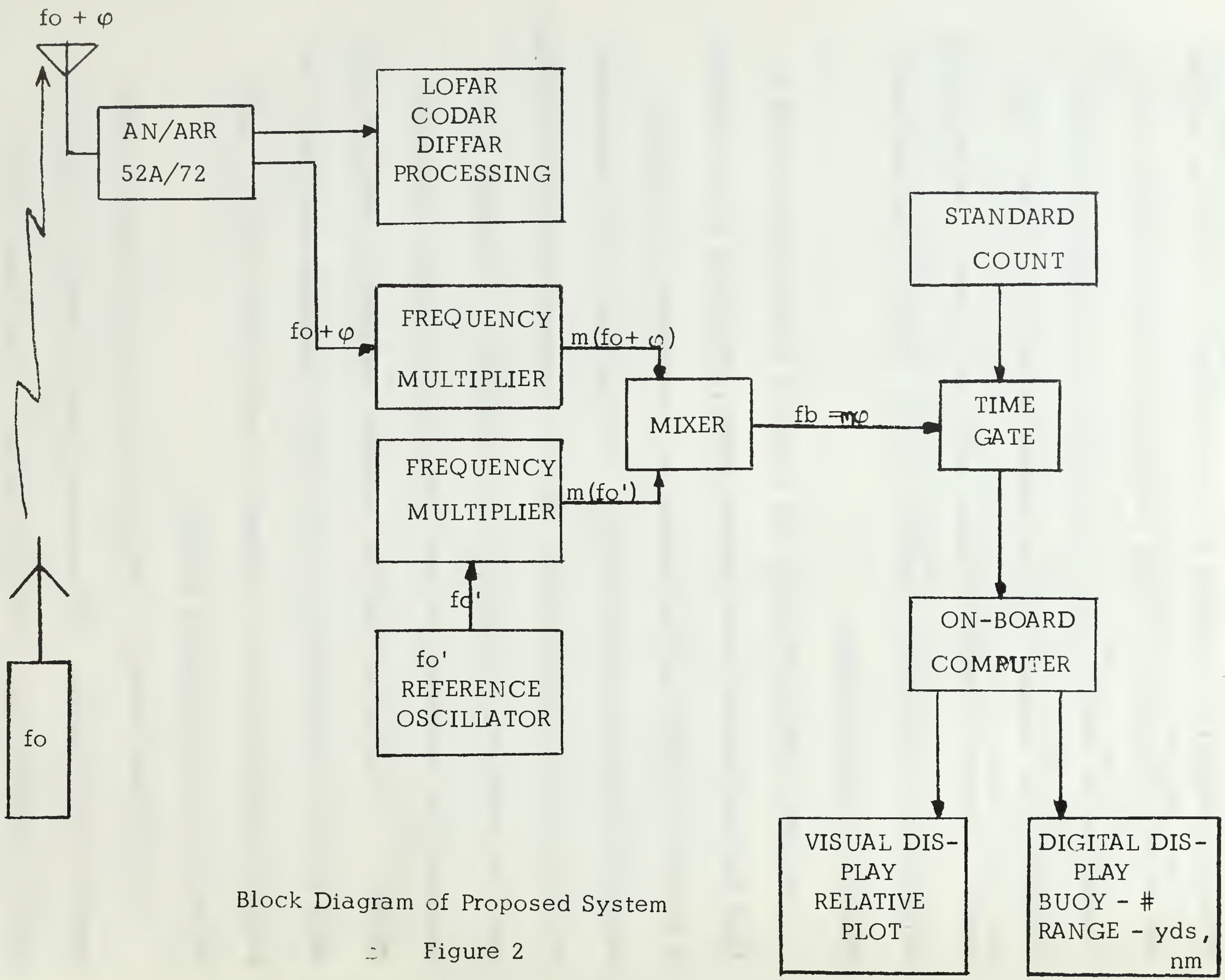
The system would take the received range signal and measure the phase by comparing it to a stable reference. The measured phase would then be fed into the on-board computer and combined with other information to fix the relative positions of the sonobuoy and aircraft. How this is to be done is discussed in detail by Cooley.[Ref. 1]

IV. SYSTEM EVALUATION

Figure 2 is a block diagram of the proposed system. In subsequent sections, several of the major system components and methods will be discussed. Of course the major concern of the system designer is in controlling the stability of the oscillators in the sonobuoy and in the aircraft so that accurate position information can be computed. The system, however, must be evaluated with cost in mind. The addition of hardware to an expendable sonobuoy must be justified by an increase in operational effectiveness.

In order to reduce the cost, the proposed system was designed to limit the modification to the present system, especially in the sonobuoy. A separate oscillator will be provided in the sonobuoy to frequency modulate the basic carrier frequency. The frequency of the range signal was chosen to be compatible with the sonic information being transmitted, and to be within the passband of the transmitter. The addition of the oscillator does increase the power requirements and this will be discussed. It is noted here that new sonobuoy designs may choose to generate the range signal from the carrier after it has been stabilized. The proposed modification was considered to be the least possible modification for existing sonobuoy designs.

In the phase measuring components on-board the aircraft, system sensitivity is important. The proposed system is designed to meet sensitivity specifications. It is also designed so that there will be no problems with lane ambiguity. This will be discussed later.



Block Diagram of Proposed System

Figure 2

V. ASPECTS OF CRYSTAL CONTROLLED FREQUENCY STABILITY

Because the system accuracy is in effect limited by the stability of the oscillator in the sonobuoy, and in part by the stability of the standard in the aircraft, the factors affecting crystal controlled frequency stability will be examined in detail. Although this area in general lacks standardization of terminology, the definitions used here are used by several leading manufacturers.

There are three contributors to frequency instability in crystal controlled oscillators. Frequency error caused by this instability is defined as the difference between the actual frequency and the nominal frequency.

$$\text{frequency error} = \Delta f = f - f_o \qquad (5\text{-}1)$$

The contributing factors will be termed frequency offset, frequency drift, and frequency deviation. It is again pointed out that these terms are not standardized, but will be used throughout this discussion. Each factor will be discussed separately to determine its effect on the proposed system.

A. FREQUENCY OFFSET

Frequency offset is defined as the difference between the actual frequency and the nominal frequency. For example, a crystal cut to 100 KHz when placed in the oscillator circuit may provide an output of 100,001 Hz. In this gross example, the frequency offset is 1 Hz. Generally this figure is normalized by dividing it by the nominal frequency and expressing it in parts per 10^n. In this example, the frequency offset would be 1 pp10^5. It will be seen later, that frequency drift can be

considered as a change in frequency offset. In this discussion, however, the term frequency offset will denote only the initial constant offset.

In the discussion of error introduced by frequency instability, it is more convient to consider the time error than the frequency or phase error. The three are related as shown in equation (5-2). The time error can then be converted to a range error using the conversion chart, Figure 4.

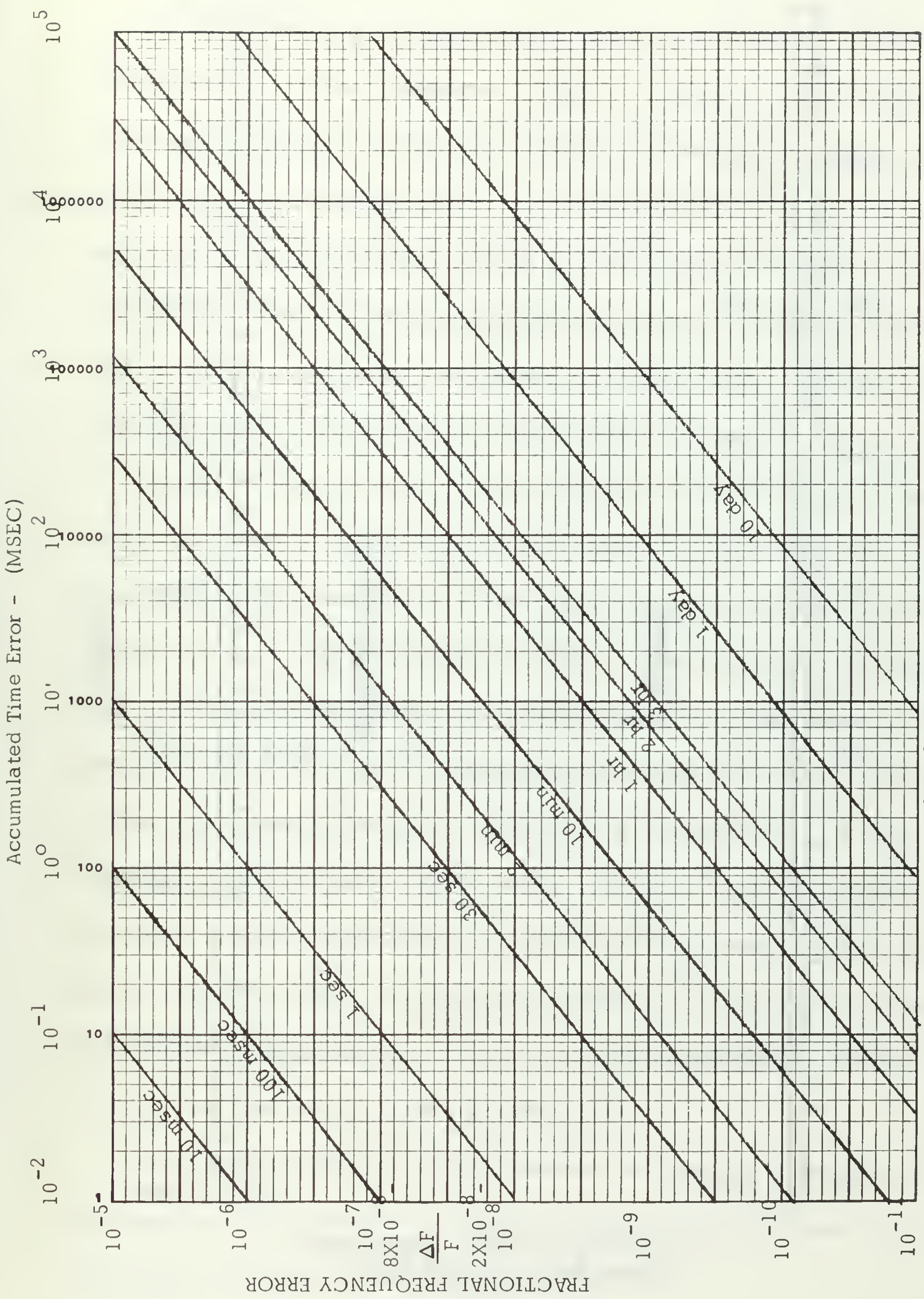
$$\frac{\Delta F}{F} = \frac{\Delta \varphi}{\varphi} = \frac{\Delta T}{T} \tag{5-2}$$

$$\Delta T = \frac{\Delta F}{F} \times T \tag{5-3}$$

As a crude example, let the frequency offset be 1 $pp10^{10}$. Entering Figure 3, it is found that in a period of one day, a time error of approximately 10 microseconds will accumulate. Using this time error and Figure 4, the accumulated range error is 3000 meters.

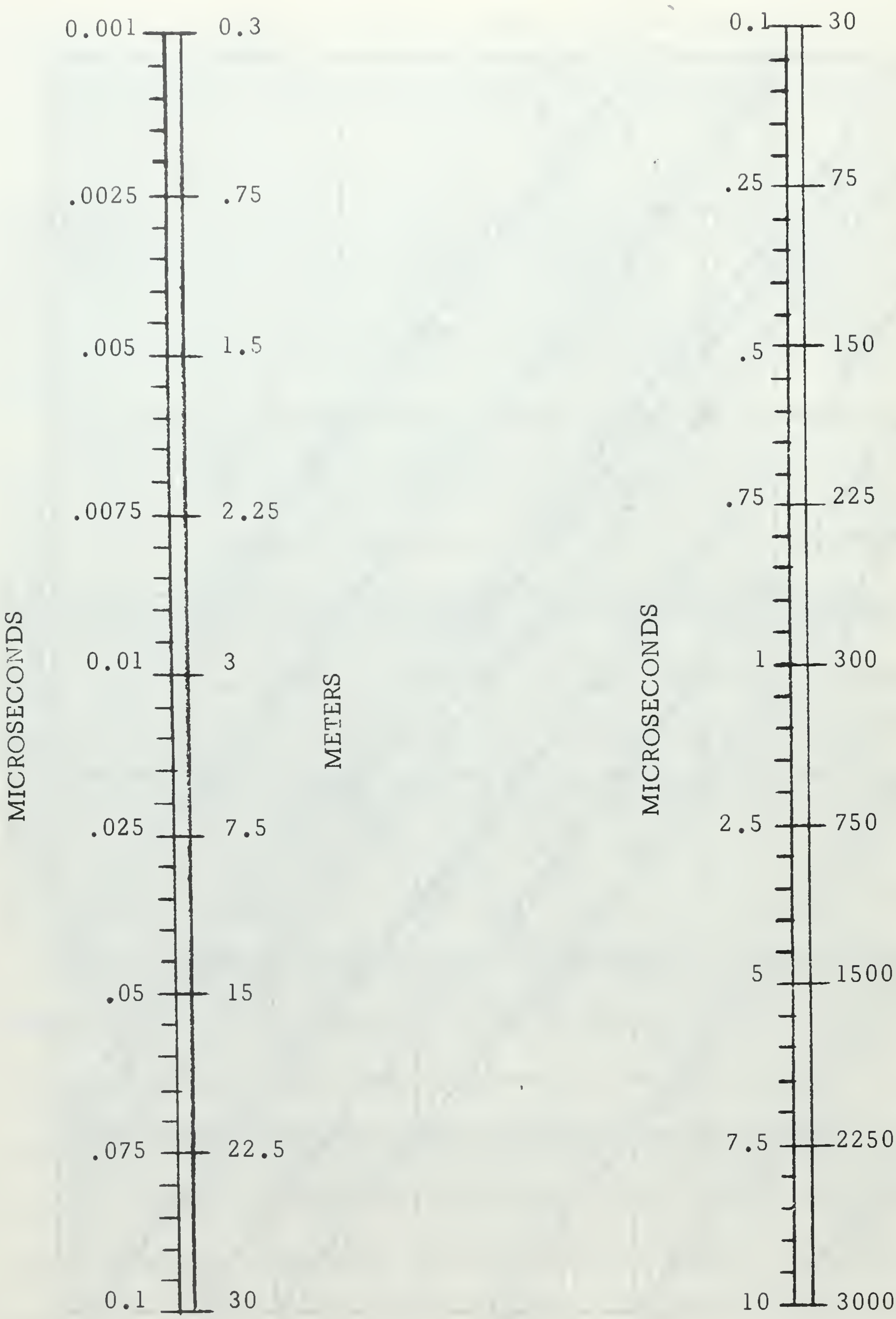
B. FREQUENCY DRIFT

An inherent characteristic of crystal oscillators is that their resonant frequency changes as they age. Frequency drift is defined as the change in frequency due to this inherent characteristic of the crystal when measured over a given period of time. The specified time interval is usually one day or longer. In well designed crystal units, the frequency drift can be assumed constant after an initial warm-up period. In frequency standards, this warm-up may take thirty days, whereas in some of the new fast warm-up crystal oscillators it may only be 5-10 minutes to reduce the drift to below the specified values.



Plot of Fractional Frequency Error vs.
Accumulated Time Error

Figure 3



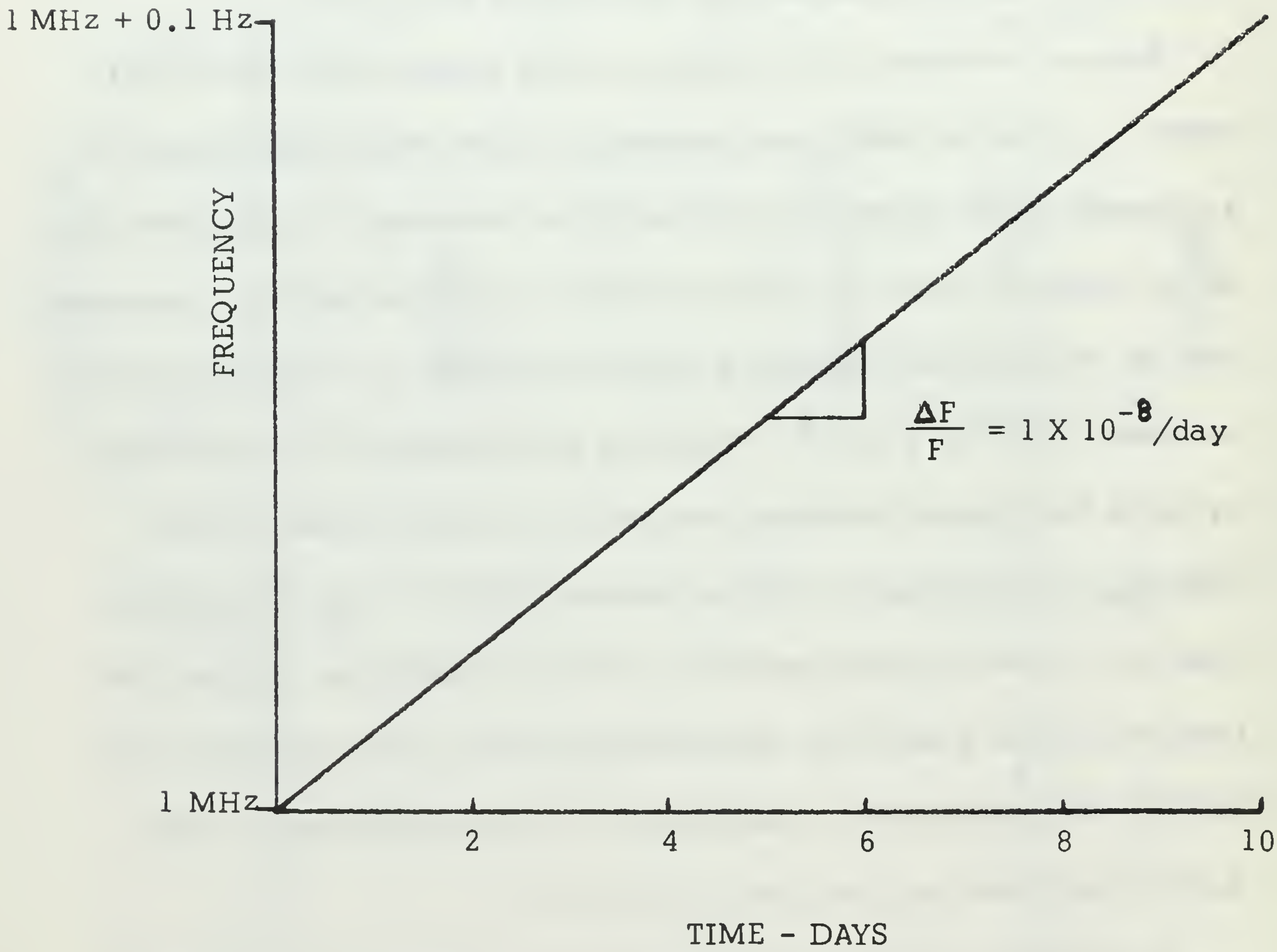
Conversion chart, Accumulated Timer Error to Range Error

Figure 4

As an illustrative example, Figure 5 shows the frequency drift of a crystal oscillator over a period of 10 days. Initially, in this example, the actual frequency and the nominal frequency are equal. This means that there is no frequency offset. It can be seen from the figure, that although the frequency drift is small (1 pp10^8/day) it accumulates with elapsed time and can result in a substantial error. The frequency at the end of one year of operation would be 1,000,003.65 hz. However, more important is the accumulated time error during this period.

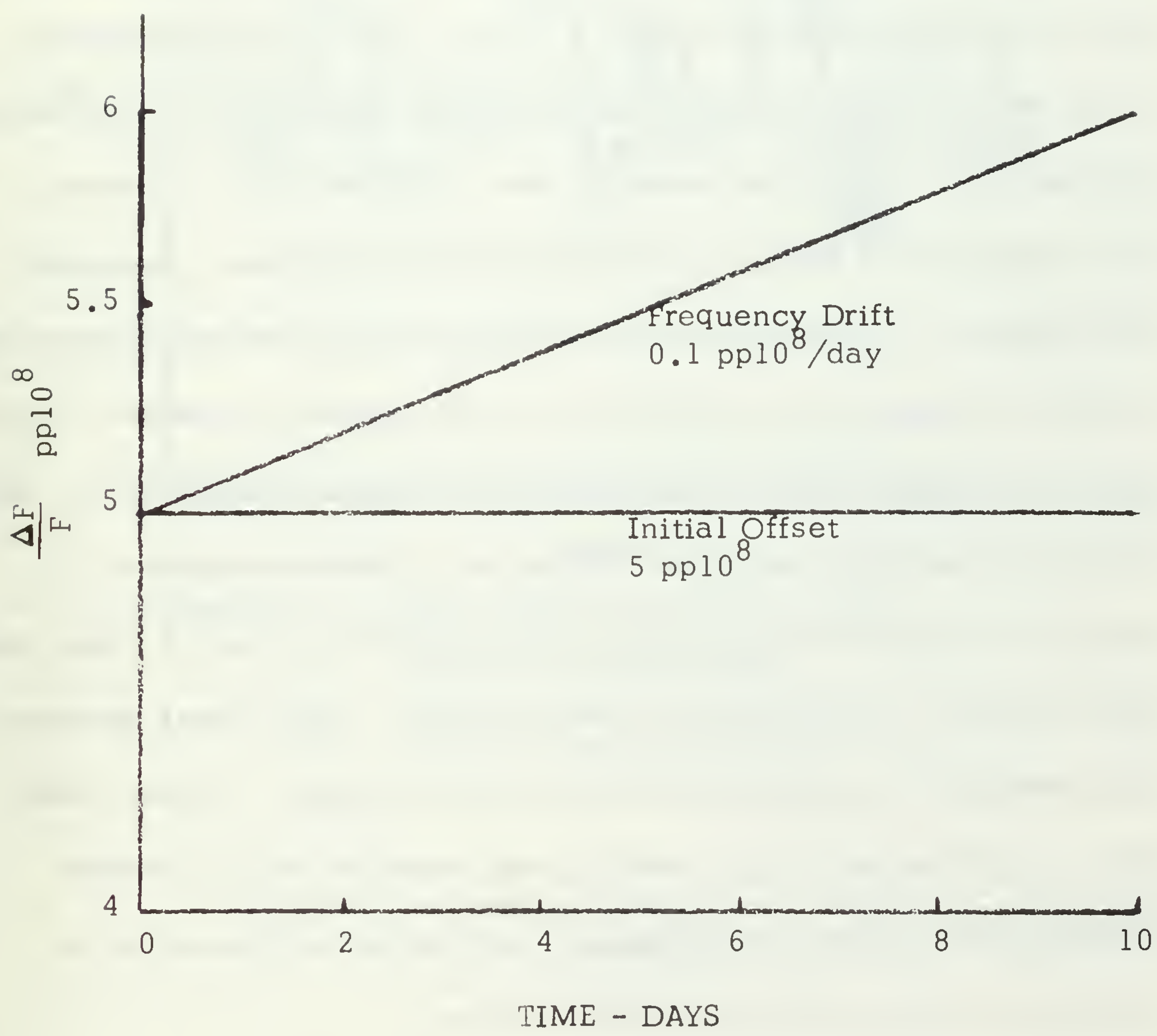
Because frequency drift can be assumed constant after the initial warm-up, it can be effectively removed from the total system error. As an example of the procedure used to remove this error, Figure 6 is a plot of the frequency drift of a given oscillator. From the figure it is apparent that the frequency drift causes an effective change in the frequency offset from 5 pp10^8 to 6 pp10^8. Frequency drift error can then be removed by using the average frequency over the 10 day time period. In this example, entering Figure 3 with a value of 5.5×10^{-8}, the accumulated time error would be approximately 4.7×10^4 microseconds. If there had been no frequency drift, the fractional frequency error would have been 5×10^{-8}, the initial offset, resulting in an accumulated time error of 4.3×10^4 microseconds over the 10 day period.

It can be seen from the above example that stability requirements are less severe in systems operating over a short period of time, than for systems operating over longer periods of time.



Typical Plot of Frequency Drift vs. Time

Figure 5



Typical Plot of Frequency Drift and Initial Offset
vs. Time

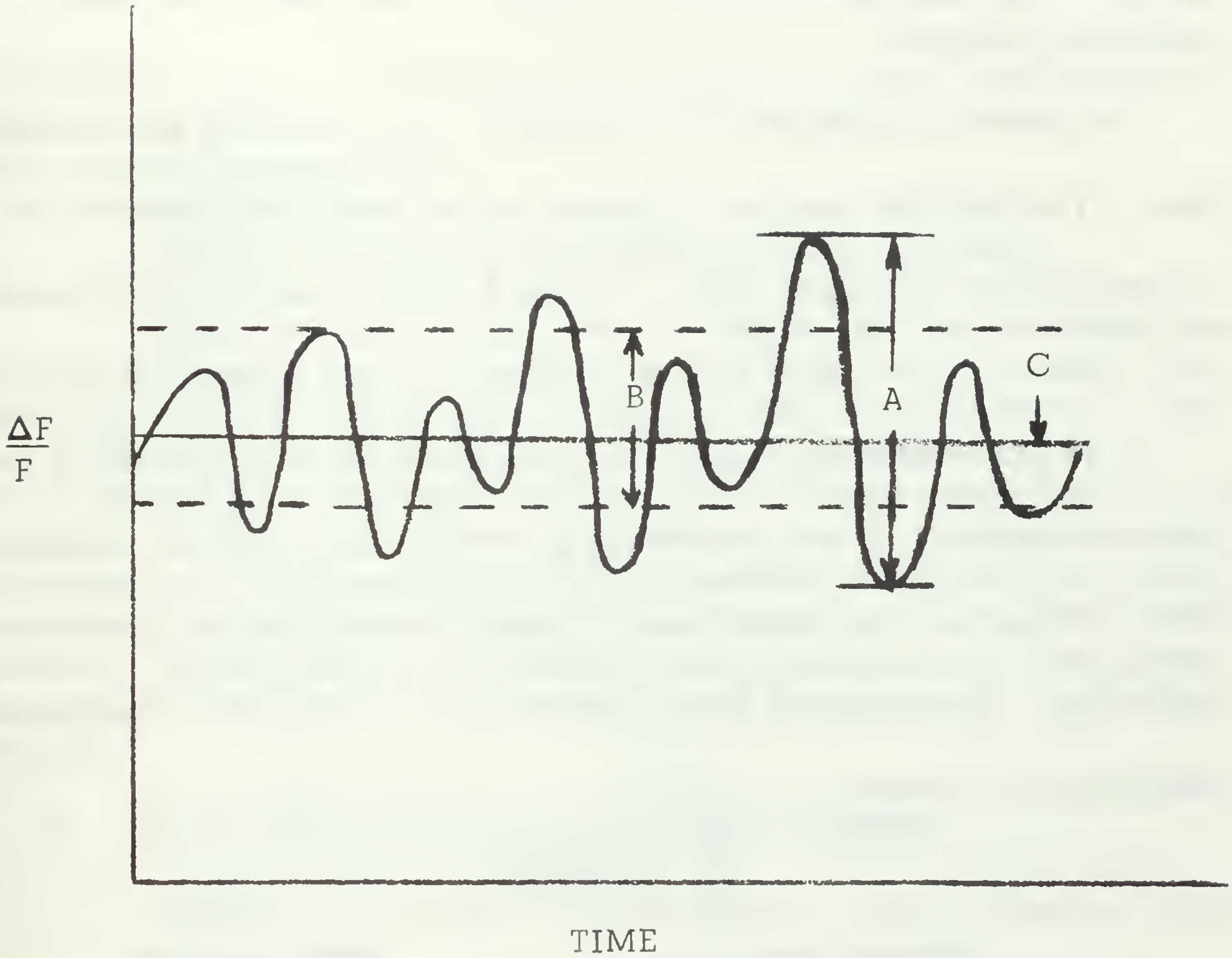
Figure 6

C. FREQUENCY DEVIATION

Frequency deviation attempts to describe the dispersion of frequency caused by unwanted components of noise and spurious signals. It is defined here as the changes in average frequency over a given time interval. The time interval must be sufficiently short so the effects of frequency drift can be considered negligible.

Since within the time interval specified above, the average frequency must approach the nominal frequency (if there was no initial frequency offset) as the averaging time is increased, the specification of frequency deviation must include the averaging time. As this time is increased, the measurement of frequency deviation becomes obscured. In general, the deviation is expressed in terms of RMS fractional frequency deviation. An RMS measurement means that 68.3% of all observed deviations will be less than the RMS value; 95.1% less than two times the RMS value, and 99.7% less than three times the RMS value. It is also important to specify the method of measurement of the deviation. Figure 7 shows the three commonly used methods of peak deviation, average peak deviation, and a straight line approximation of the peak deviation. Systems which rely on excellent short term stability, and therefore require accurate knowledge of the frequency deviation, must be sure of the method of measurement when considering specifications.

The causes of frequency deviation can be separated into three sources. These contributors to the overall frequency deviation are (1) thermal and shot noise within the oscillator which perturb the



Method A. Peak Deviation per given time

B. Average Peak Deviations

C. Straight Line Approximation

Typical Plot of Frequency Deviation, Illustrating Measurement Methods

Figure 7

oscillations, (2) additive noise associated with the accessory circuits which does not perturb the oscillations but adds to the signal, and (3) oscillator fluctuations due to changes in the crystal unit or circuit parameter changes.

As pointed out before, the deviation is a function of the averaging time. The first two sources of deviation are effectively removed by increasing the averaging time. The third source, known as flicker noise or 1/f noise, is the major source of error in longer periods of averaging.

It is apparent that if there is an accumulated error caused by frequency deviation, it will appear as a contribution to the total frequency drift. Table V.I is a typical manufacturer's specification of frequency deviation. For averaging times greater than 0.1 seconds, the frequency deviation is constant.

TABLE V.I

average time	RMS fractional frequency deviation
1 msec	8.0×10^{-10}
10 msec	1.5×10^{-10}
0.1 sec	1.5×10^{-11}
1.0 sec	1.5×10^{-11}
10 sec	1.5×10^{-11}

Instabilities greater than 1.5×10^{-11} exist for such a short period of averaging time, their effect on accumulated error is small. The "steady-state" value can be used to remove the accumulated error over longer periods of time.

D. FACTORS CONTRIBUTING TO THE DEGRADATION OF FREQUENCY STABILITY

There are three primary sources of stability degradation in crystal oscillators. They are variations in the circuit voltage, load impedance, and operating temperature.

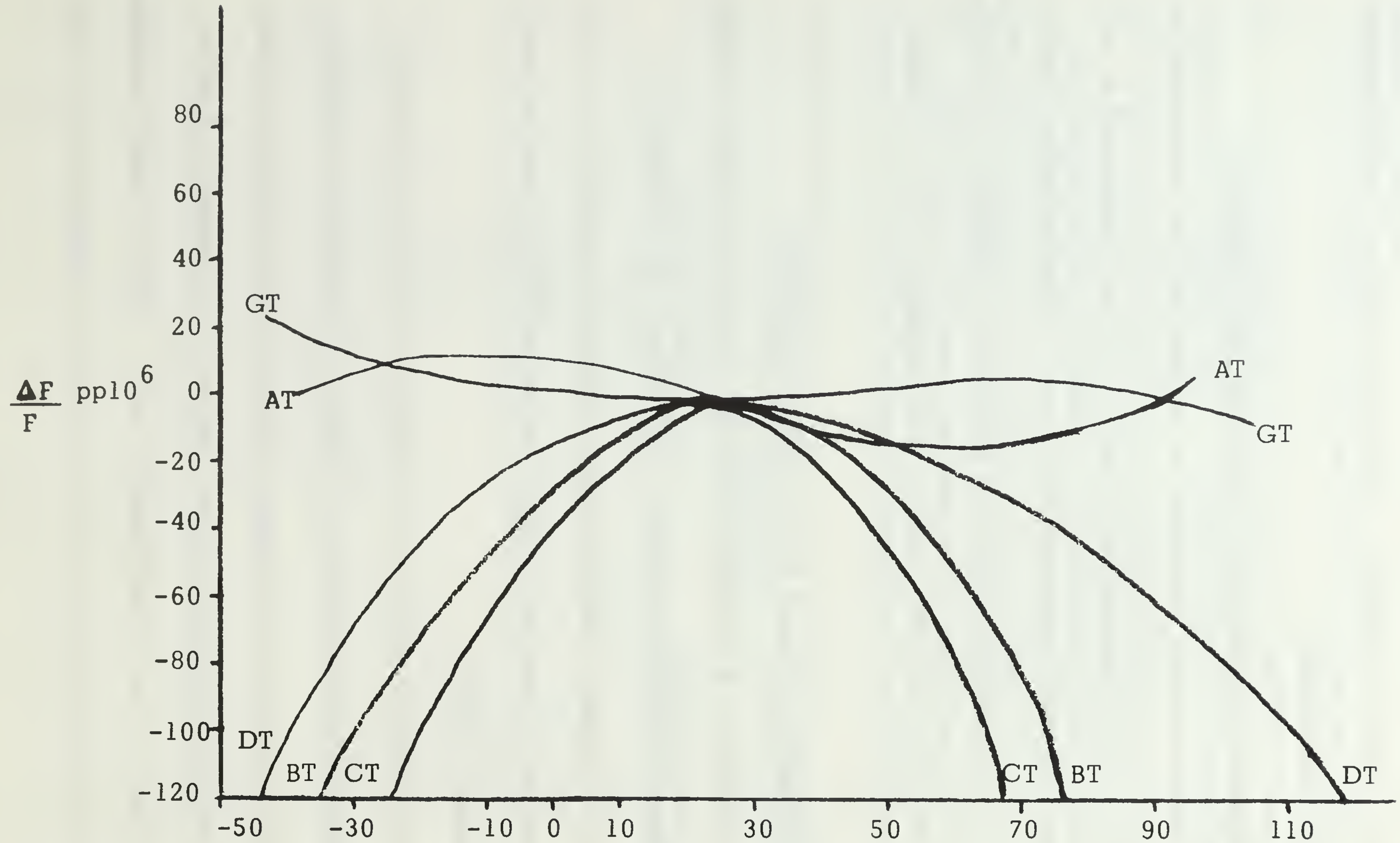
1. Degradation Caused by Voltage and Load Variations

Frequency errors introduced by voltage and load variations are insignificant in well designed oscillators. The incorporation of a voltage regulator (usually Zener regulation) and a buffer amplifier in the output stage, has practically eliminated degradation of stability from these sources. These features are normally self-contained in the oscillator package.

2. Degradation Caused by Temperature Variation

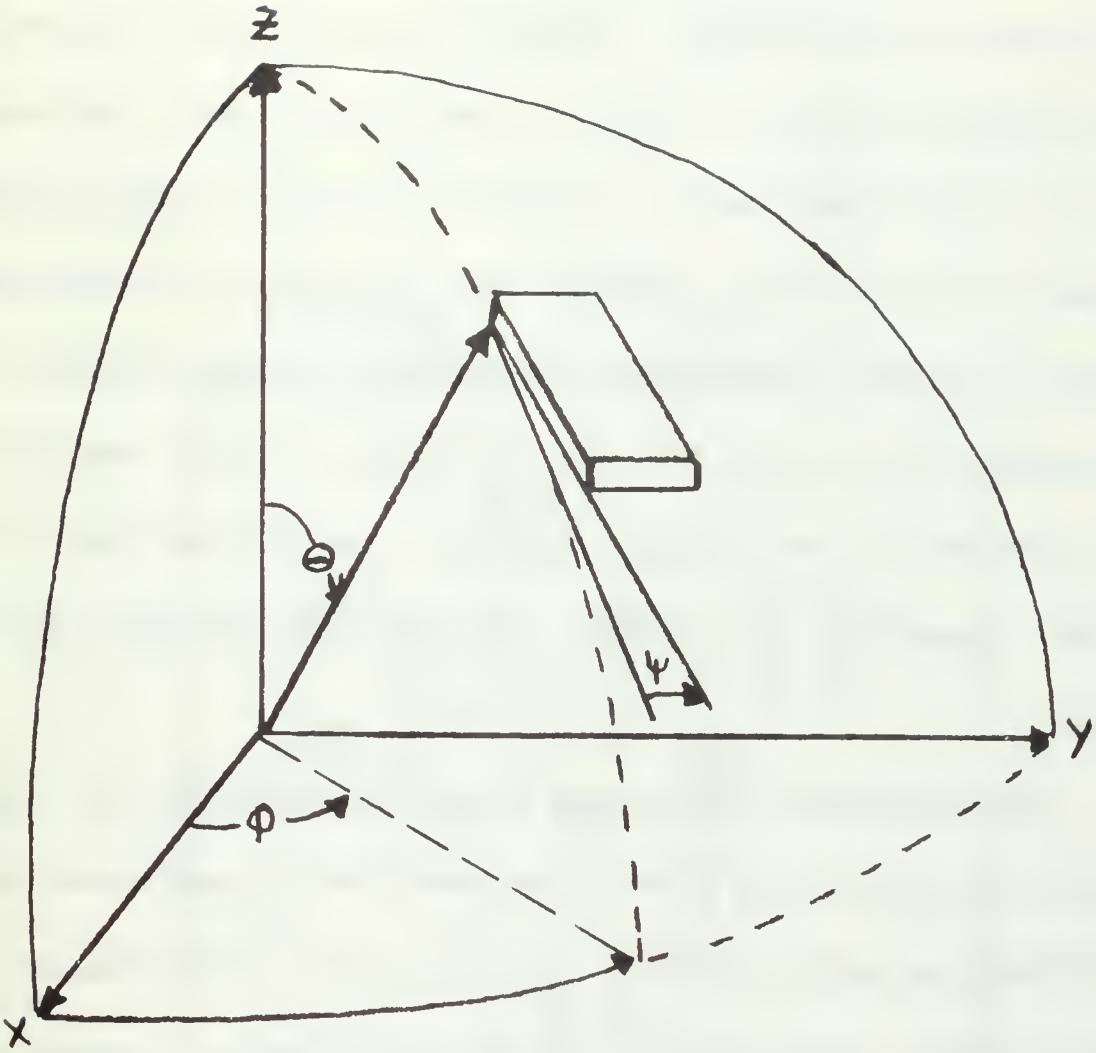
Variations in the operating temperature have pronounced effects on the frequency stability of crystal oscillators. The instability is reflected by a change in the frequency. Because the problem is not as easily solved as for load and voltage variations, the temperature effect will be treated in detail.

Just as quartz crystals inherently age, they also inherently change frequency when subjected to changes in operating temperature. Shown in Figure 8 are the frequency-temperature characteristics of the commonly used crystal cuts. Figure 9 shows the orientation of these cuts with respect to the crystallographic axis. Without going into detail, it is pointed out that the point of inflection on the frequency-temperature



Typical Plot of Frequency-Temperature Characteristics of
Common Crystal Cuts

Figure 8



NAME	φ	θ	Ψ
X	0	90°	90°
Y	90°	90°	90°
AT	-90°	54-3/4°	90°
BT	-90°	-41°	90°
CT	-90°	52°	90°
GT	-90°	38°52'	±45°
MT	6°40'	50°28'	79°36'
NT	9°26'	40°40'	77°40'

Orientation of Common Crystal Cuts

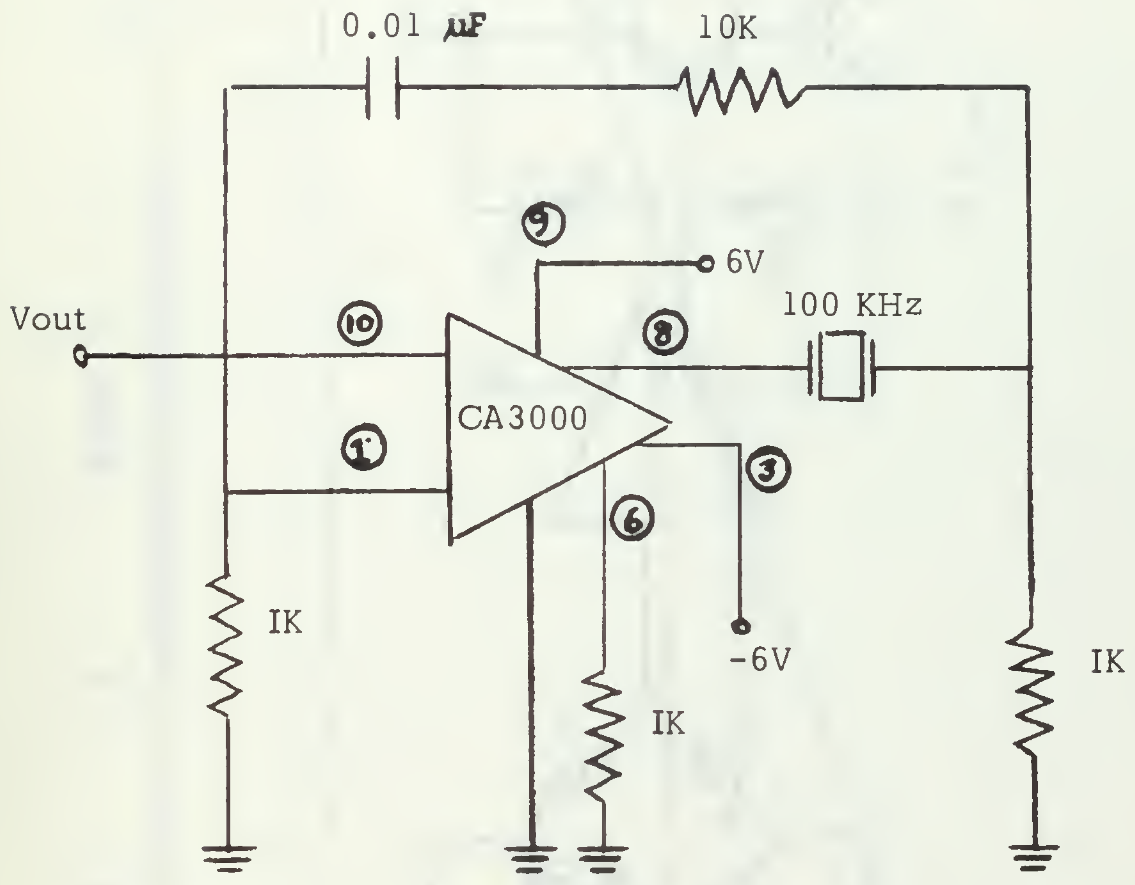
Figure 9

characteristics of most crystal cuts can be placed at any temperature by proper choice of dimensions or orientation of the crystal.

To understand more clearly the effect of temperature on frequency stability, a frequency-temperature characteristic curve was determined for a low cost 100 KHz crystal. Figure 10 is a schematic diagram of the oscillator built for this test. Figure 11 shows the crystal oven designed and built for this determination. Using an electronic counter to measure the period of the oscillator, and averaging 10^5 periods, a measurement sensitivity of 1 pp10^7 was obtained (manufacturer's specification). The oven temperature was controlled over a temperature range from 22°C to 45°C. A cooling unit was used to control the temperature from 21°C to 0°C. Both temperature control units were constant to within ±0.1°C once set.

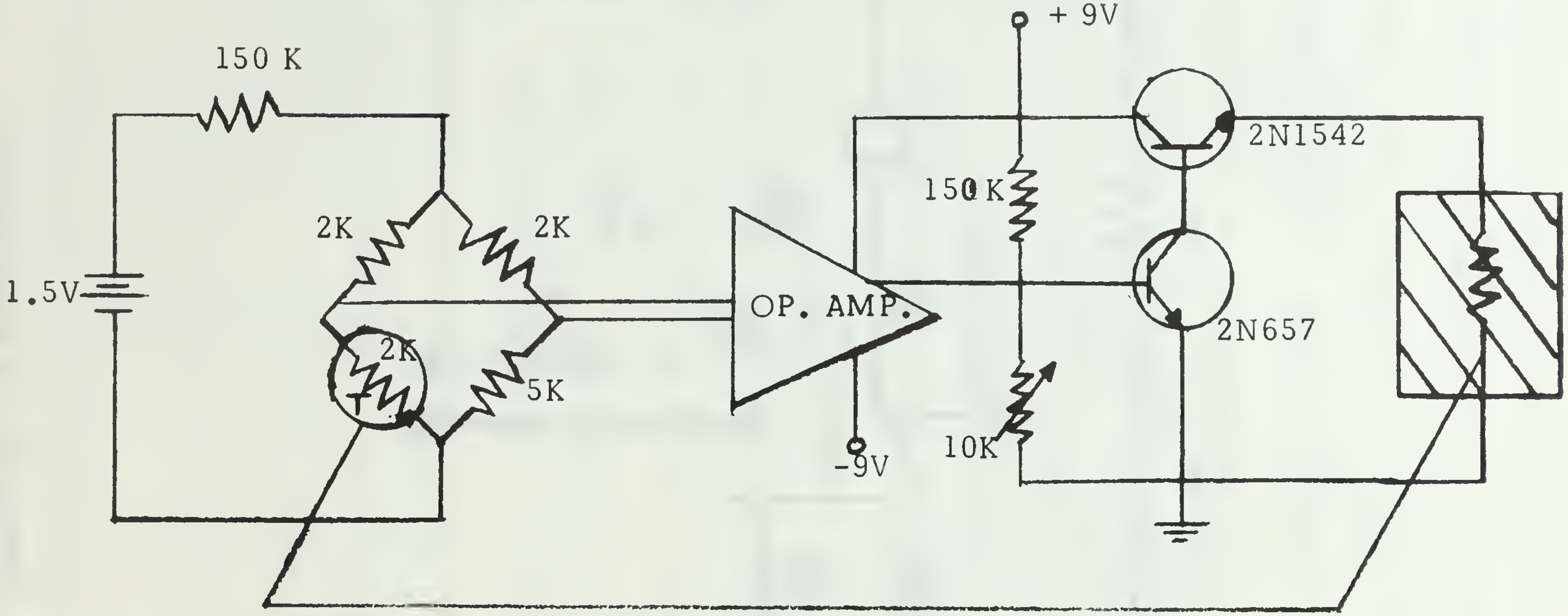
The procedure followed was to set the temperature control and then after allowing 8 hours to stabilize (stabilization was accomplished in a much shorter period of time), 100 consecutive measurements of the period were made. The average value was calculated and plotted in Figure 12. From the characteristic curve, it was concluded that the crystal was an AT cut. No specification on the crystal was available to verify this conclusion. It was found that the crystal frequency could be held to within ±2 pp10^7 by controlling the temperature to within ±0.1°C.

The oscillator contained in the sonobuoy is the most critical system component. It is also the component most sensitive to



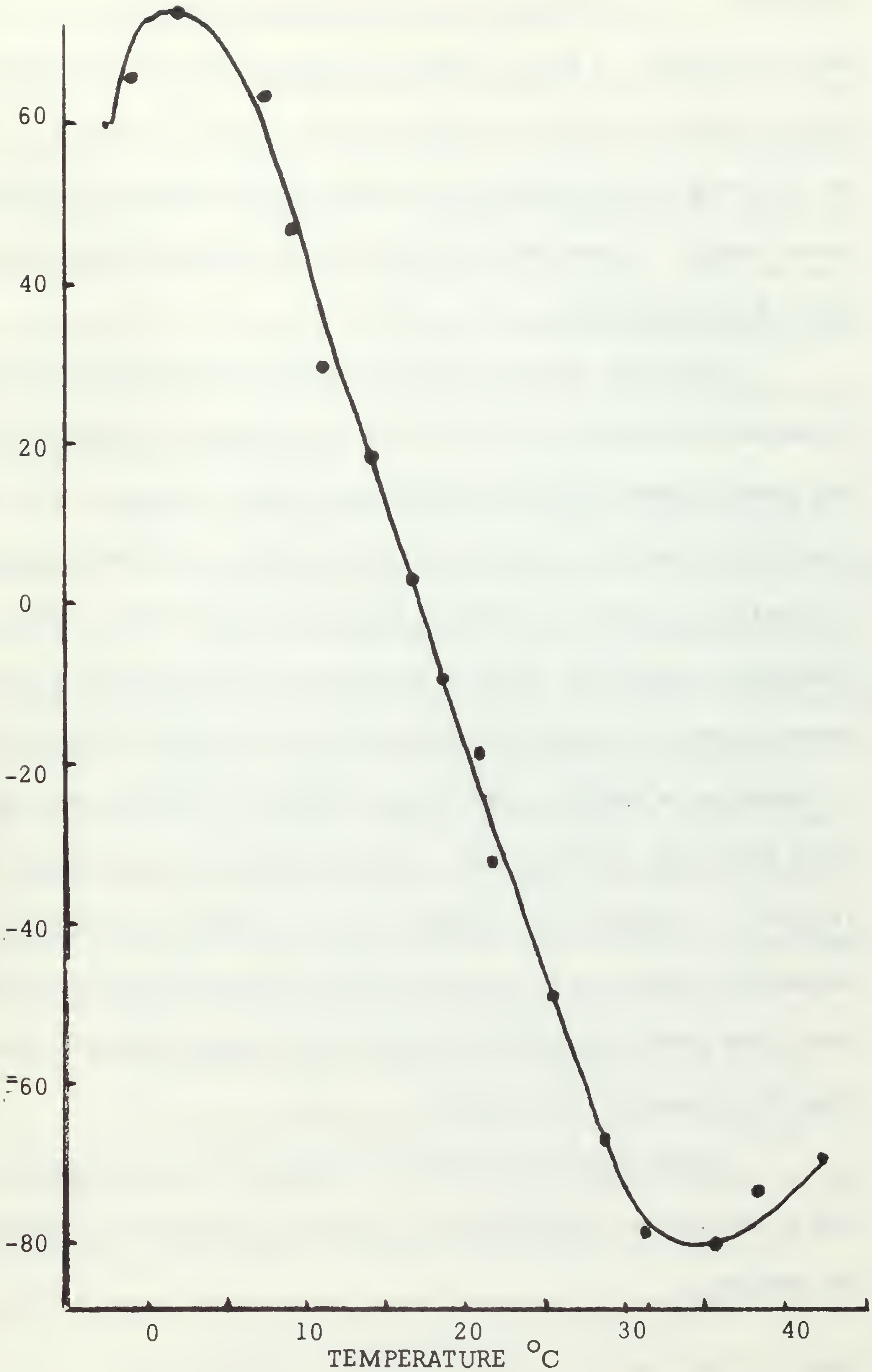
Circuit for 100 KHz Oscillator

Figure 10



Circuit for Crystal Oven

Figure 11



Frequency-Temperature Characteristics for a
100 KHz Oscillator

Figure 12

temperature, and unfortunately, the component most exposed to temperature variations. It must be able to function within specifications during ambient temperature variations from about $2^{o}C$ to $30^{o}C$. It must be relatively low powered in any configuration because of the limited power supply. It must be reasonably priced when purchased in volume since it is expendable.

The set of curves used to determine the accumulated error from frequency offset and drift can be used by the system designer in choosing the proper crystal unit when considering system accuracy. It is not possible to construct a meaningful set of graphs to determine the accumulated error caused by operating temperature variations. Most crystal oscillators specify the effect of temperature on stability by giving the maximum expected fractional frequency error over the temperature range. For example, a stability specification might be $\pm$ .005% over a temperature range from $-40^{o}C$ to $70^{o}C$. More stable units are usually specified in $pp10^{n}$. In general, the stability can be improved by reducing the temperature range. If the oscillator could be held exactly at one temperature, the offset could be determined at that temperature and removed from the system as shown before.

Crystal oscillator designs incorporate either temperature control or temperature compensation to lessen the influence of temperature on stability.

a. Temperature Control With a Crystal Oven

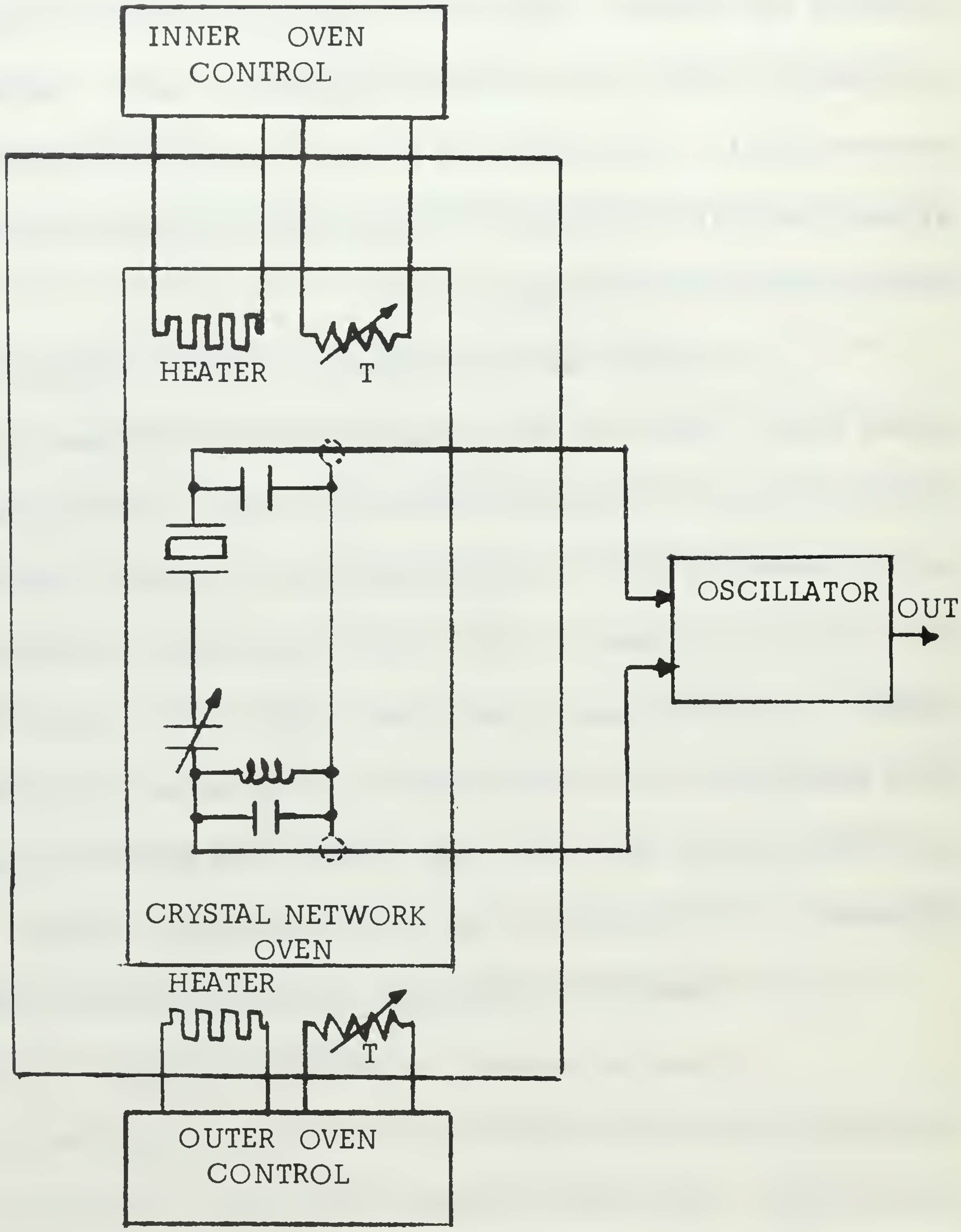
In order to obtain the highest stability that today's precision oscillators are capable of providing, an oven is used to control the operating temperature. Figure 13 is a schematic diagram of a dual proportional oven used in many of the high precision units. The amount of power required by the oven is, of course, related to the operating and ambient temperature difference. Oven and crystal warm-up times are determined by the oven design.

The use of an oven insures the highest stability as mentioned above. Once set, dual proportional ovens are in some cases stable to within $0.001^{\circ}C$. With this temperature control, the frequency error can be determined at the operating temperature, and will remain constant while the oven maintains control. Other oven designs provide less control, but usually require less power. Figure 14 is a graph of the input power versus the ambient temperature for various cavity temperatures for a typical oven unit. Also shown on the graph is the maximum allowable cavity dissipation if the oven is to maintain control.

b. Temperature Compensated Crystal Oscillators, TCXOs

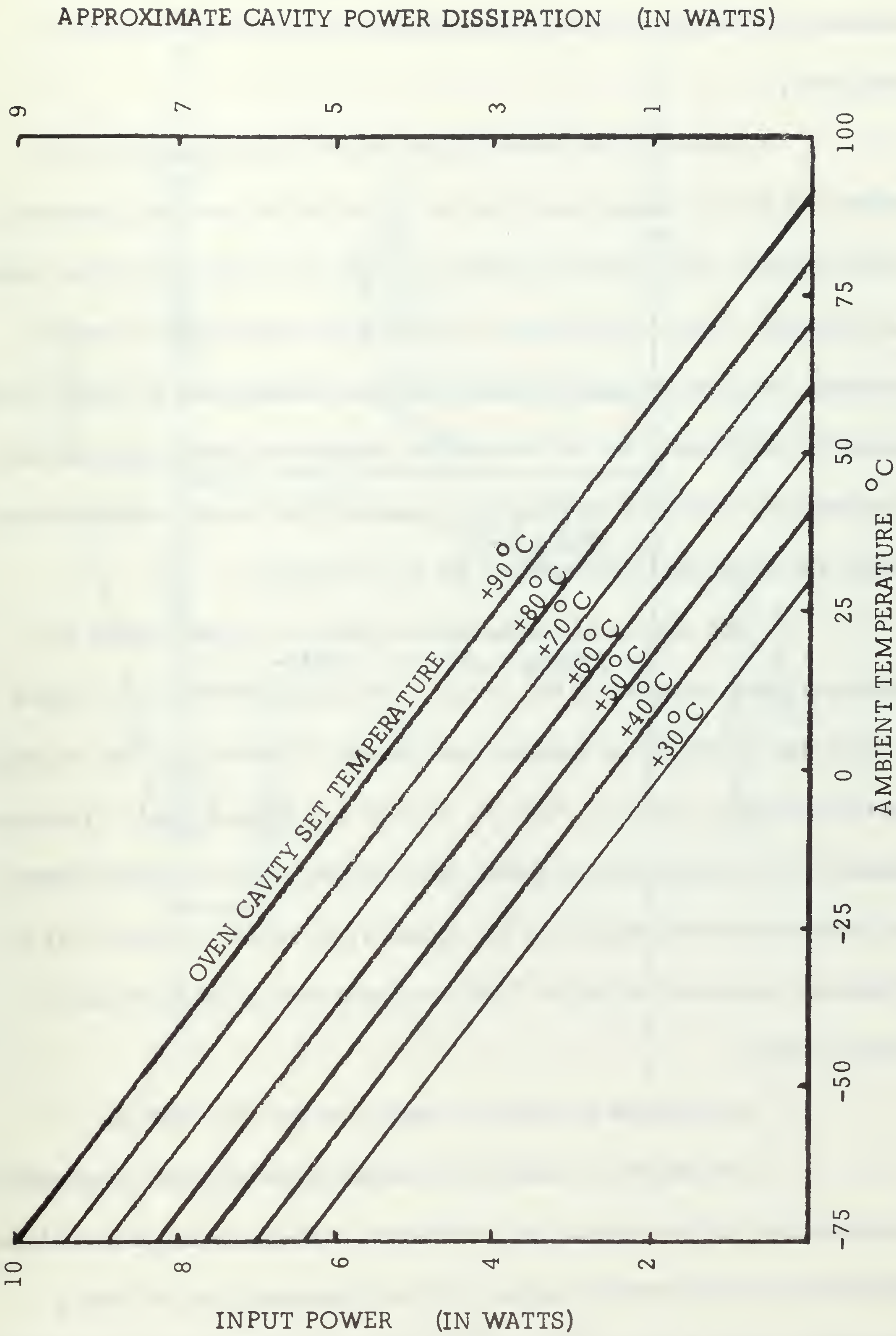
As may be expected, the effect of a change in the operating temperature of a crystal is to vary the mechanical stresses in the crystal itself. These stress variations then cause a change in the resonant frequency of the crystal, and consequently a frequency error.

There are two methods of temperature compensation, mechanical and electrical . The electronic method, utilizing variable



Typical Dual Proportional Oven Circuit

Figure 13



Oven Input Power vs. Ambient Temperature

Figure 14

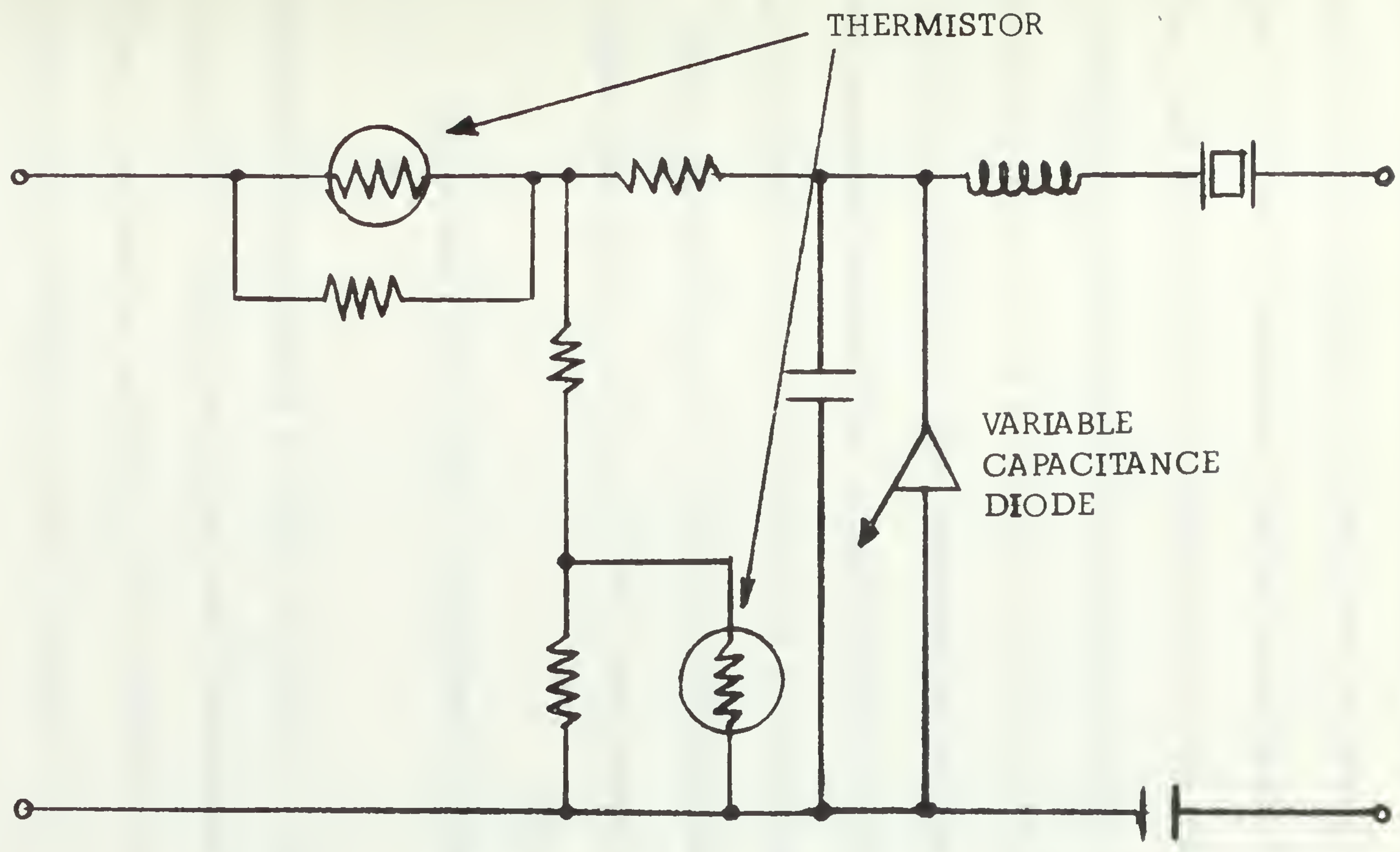
capacitance diodes to control the frequency, has proven much more successful. For this reason, mechanical compensation will not be discussed.

The effect of increasing or decreasing the mechanical stress in a quartz crystal structure is to change the resonant frequency of the crystal. This can be equated to a change in capacity of the equivalent circuit. Once this variation of equivalent capacitance versus operating temperature has been determined, a varicap can be added to the circuit to compensate for the changes in equivalent crystal capacitance. Thermistors are used in the circuit as temperature sensing elements and control the necessary bias voltage for the varicaps.

The degree of compensation depends on the number of thermistors and varicaps in the circuit. The design of TCXOs is aided by computer synthesis to optimize the choice of thermistors and varicaps and their range of control. Newell, Hinnah and Bangert [Ref. 3] discuss temperature compensation in detail, and develop a set of design curves and circuit parameter equations for simple TCXO units. Figure 15 is a schematic diagram of a typical TCXO utilizing two thermistors and a single varicap.

c. Advantages and Disadvantages of the Two Methods

The degree of stability obtained by temperature compensation is not as good as that which can be obtained with an oven. State-of-the-art TCXO units have been reported with stabilities of 1 pp10^7 over a temperature range from -40°C to 70°C. This is several orders of magnitude



Typical TCXO Circuit (5-13)

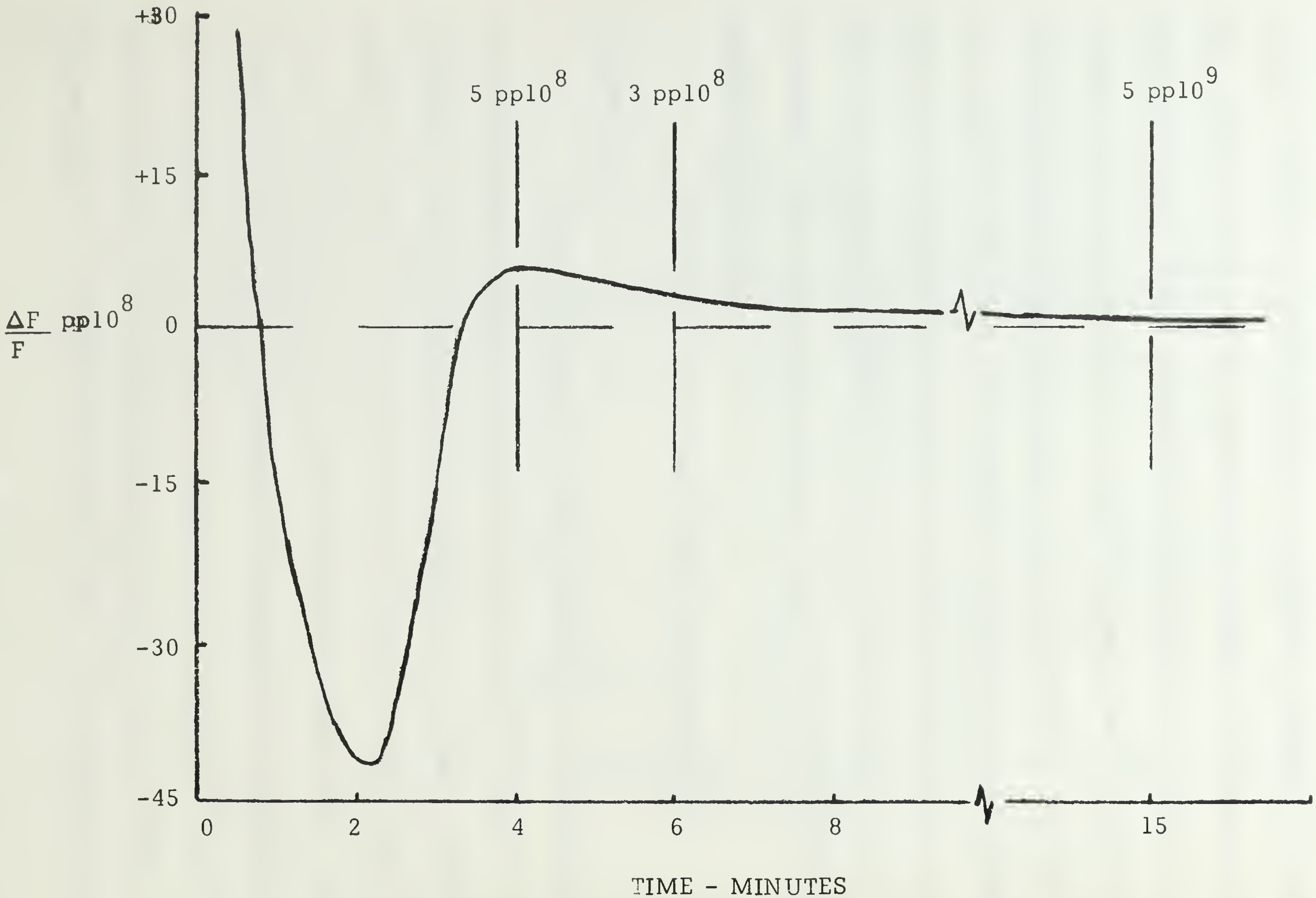
Figure 15

less than the stability obtainable with an oven. There are obvious advantages to using TCXOs, however, in certain situations. First, there is no warm-up required which may be desirable for a given application. The power requirement for the compensating network is negligible, so the overall power requirement is practically the same as for a simple oscillator. Also, because the crystal operates at ambient temperatures, the frequency drift rate, which for most crystal cuts increases with increasing operating temperature, will be a minimum. On the other hand, crystal ovens have been designed with reduced warm-up periods. Figure 16 is a manufacturer's specification for a fast warm-up oven. This series provides stability of 5 pp10^9 in 15 minutes and 5 pp10^8 in 4 minutes. These figures are at least an order of magnitude better than available TCXO units.

d. Combining Temperature Control and Temperature Compensation

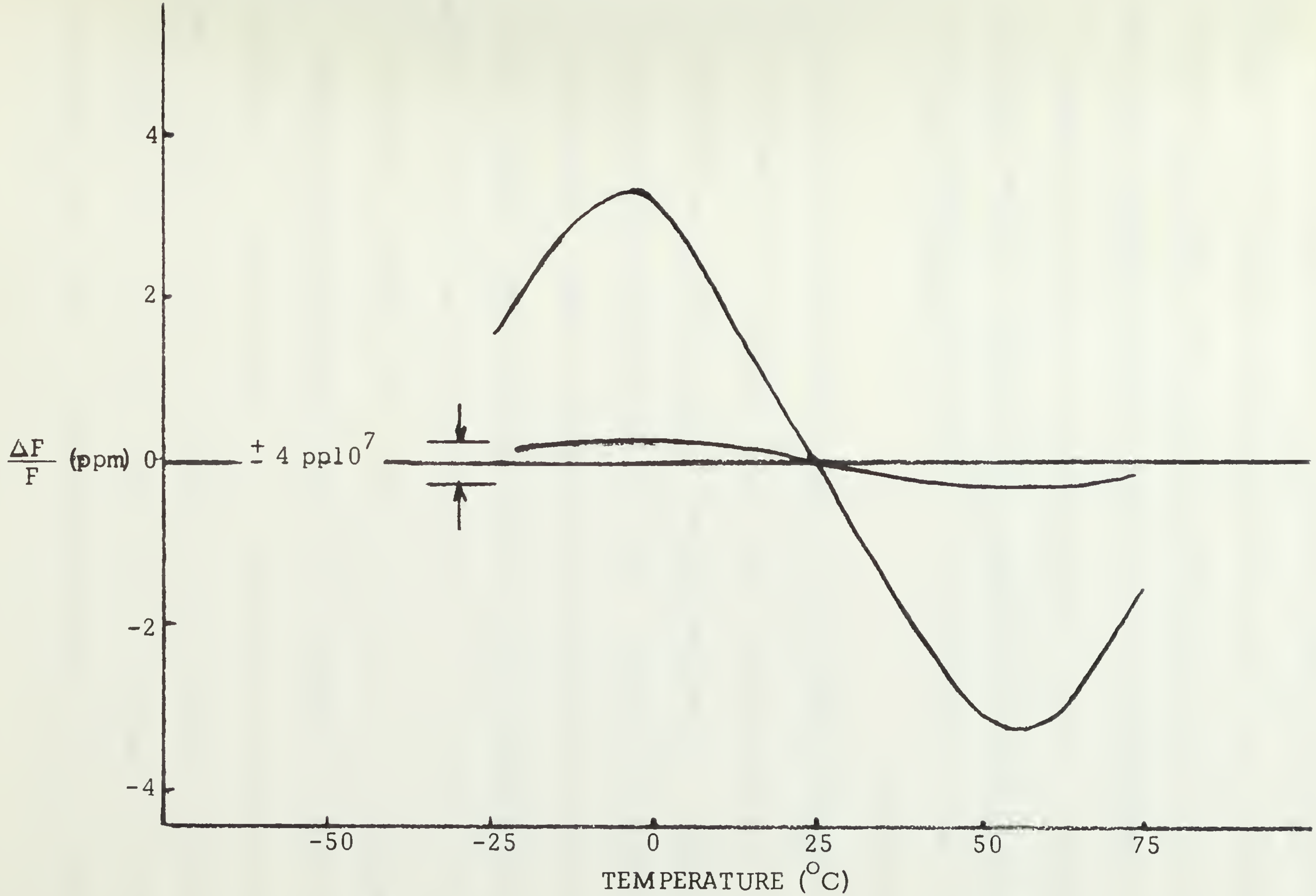
Figure 17 shows the effect of temperature compensation on the frequency-temperature characteristics of an AT cut crystal. From the figure, it can be seen that if the operating temperature of the TCXO is held to within $\pm$ 10°C (around 25°C), its stability will be equal to that of an oven, whose temperature control must be less than $\pm$ 1°C. This suggests the possibility of combining a temperature compensation network and a temperature control unit, to obtain the advantages of both. The power requirement and warm-up time of the oven would be reduced, and the stability of the TCXO would be increased. This possibility should be

investigated thoroughly in this system design because of the limited power available, and the fast warm-up time and high stability desired.



Fractional Frequency Error vs. Time for FS Series Oscillators

Figure 16



Frequency-Temperature Charachteristics for an Uncompensated and a Compensated Crystal

Figure 17

VI. THE TRANSMITTED RANGE SIGNAL

Several papers have been recently written, discussing a buoy mounted short range navigational system. These papers discuss in detail the frequency stability requirements [Ref. 2], and the receiver design [Ref. 4]. The basic system proposal in the short range navigation system is similiar to the sonobuoy ranging system. Both systems would rely on a geographic grid set up by the stable radio signals as discussed in Section 2. The buoy mounted navigational system would require two transmitting buoys since position, not just range, is desired. The buoys would transmit unmodulated RF for reception and comparison on-board a ship in the area.

An important difference in the two systems is the use of an unmodulated signal for the range signal versus modulating the carrier with the range signal. The sonobuoy system requires identification of the sonobuoys for tactical reasons. This is accomplished by having each sonobuoy transmit on a different carrier frequency. If the range signal was derived or generated from the carrier frequency after it had been stabilized, it would require 16-32 different generating packages (assuming the range signal is to be of one frequency). If the generating network was standard for all sonobuoys, for example dividing the carrier frequency by 100 to reduce the lane problem, then it would require 16-32 different frequencies be generated from the reference on-board the aircraft. Simply stabilizing the carrier and making phase comparisons at this frequency, would result in lane widths of about 2 meters. The aircraft would pass

in and out of a lane in a period of time comparable to the shortest measurement time. This would render the system useless unless appropriate frequency division was used.

As mentioned before, the system was designed to limit the modification of the sonobuoy and to limit the amount of additional hardware which would have to be added to this expendable unit. It was therefore decided to frequency modulate the basic carrier frequency of each sonobuoy with the same range signal frequency by means of an additional oscillator. This would mean a simplified system, and reduced cost because of standardization.

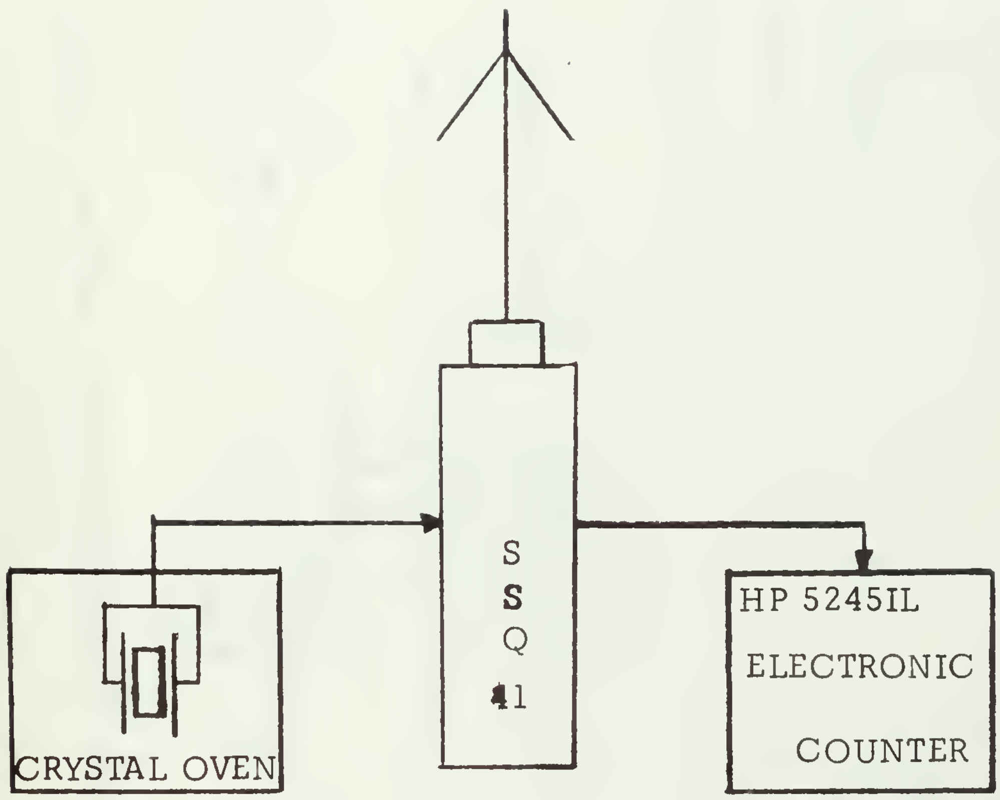
VII. CARRIER STABILITY -- AFFECT ON RANGE SIGNAL

A test was devised to determine whether or not the carrier stability would affect the stability of the range signal. For this test, the crystal controlling the carrier frequency was removed from the sonobuoy and placed in the oven. Figure 18 is a block diagram of the test setup. The nominal frequency was 21.298744 MHz. The oven temperature was varied from 25°C to 45°C. The carrier frequency was observed to shift from 21.298744 MHz to 21.298626 MHz during this temperature variation. The total variation was 118 Hz or 5.9 Hz/°C. The test setup was then modified as shown in Figure 19. A TS-382 C/U Audio Oscillator was used to modulate the carrier at 4KHz. The signal was received with an AN/URR 27 Radio Receiving Set and phase compared with the modulating signal using a Linear Phase Detector. Simultaneously, the carrier frequency was monitered as before. The same temperature variation was used.

The phase relationship of the modulating signal and the received signal was independent of the carrier frequency shift throughout the temperature variation.

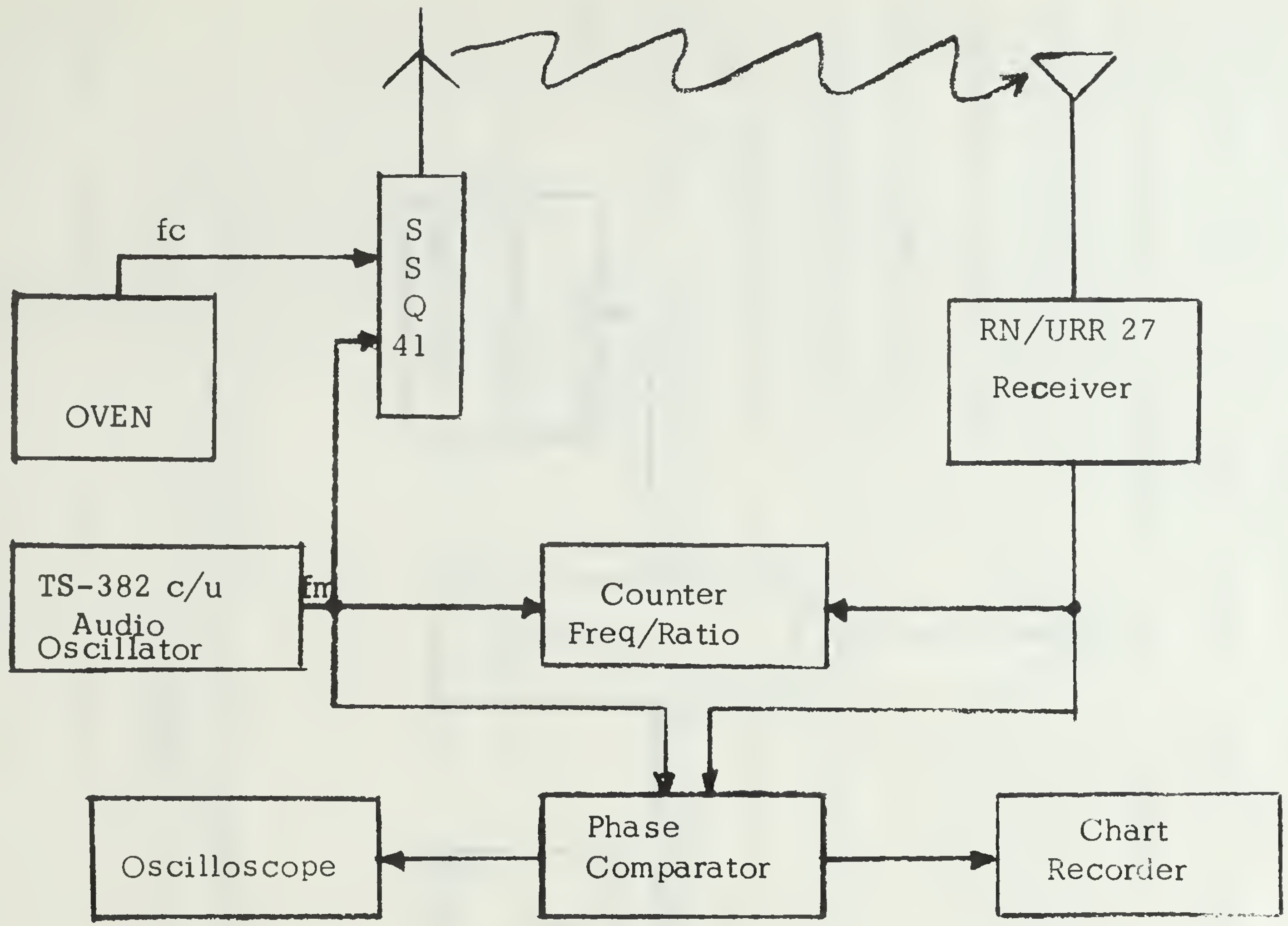
A. DISCUSSION OF TEST RESULTS

This test verified an important aspect of the proposed system. A stable range signal in the frequency range from 16-4000 Hz (within the passband of the transmitter) could be used to determine the slant range to the sonobuoy. Preferrably, this signal should be outside the area of interest to acoustic analysis. For this reason, 4 KHz was chosen.



Block Diagram of Carrier Stability Test

Figure 18



Block Diagram of Frequency Modulation Stability Test

Figure 19

The proposed system would require only one modification to the present sonobuoys. The addition of the 4 KHz stable oscillator would be the same for each sonobuoy regardless of carrier frequency. A 4 KHz detector must be added to the receiver in the aircraft to remove the range signal for phase comparison. At 4 KHz the lane width would be 75,000 meters. With this width, lane ambiguity would be no problem, and this would mean less complexity in the aircraft equipment.

VIII. MEASUREMENT SENSITIVITY

The use of frequency multipliers to multiply the accumulated phase of the range signal, in order to increase the sensitivity of the measurement, was investigated. Because a range signal frequency of 4 KHz was chosen, even large changes in range will be reflected as small changes in the phase of the received signal. A range of 750 meters would be obtained from a phase difference of 3.6 degrees. Assuming a desired accuracy in the measurement system of $\pm$ 7.5 meters, the system would have to be able to measure .036 degrees of phase difference at 4 KHz. If the frequency were multiplied and the phase measurement made at a higher frequency, the same accuracy could be obtained without the necessity of measuring such small differences. This, in effect, increases the sensitivity of the measurement system.

A great amount of research in this area of frequency multiplication has been sponsored by the Frequency Control Division, Electronic Components Research Department, U. S. Army Signal and Development Laboratory. One such contract, reported quarterly from July 1, 1960 to April 1, 1961, by New York University proves to be an exhaustive research of the problem. The results will be reviewed here for consideration in the proposed system. Complete discussion is found in the reports [Refs. 5, 6, 7, and 8].

Introduced in the reports is an uncertainty factor, h, defined as the product of the maximum error and the observation time. Table VIII.1 is a summary of the findings presented in the reports. The effect of a

1. The basic Frequency Measuring System

$$h = \Delta\Phi + Wa\,\Delta To$$

2. The basic Frequency Measuring System with an ideal multiplier

$$h = \Delta\Phi / M + Wa\,\Delta To$$

3. The basic Frequency Measuring System with a non-ideal multiplier

$$h = \Delta\Phi / M + Wa\,\Delta To + 2\pi\,\Delta W/Wa$$

4. The Heterodyne Frequency Measuring System with an ideal multiplier

$$h = \Delta\Phi / M + (Wa - Wr)\,\Delta To$$

5. The Heterodyne Frequency Measuring System with a non-ideal multiplier

$$h = \Delta\Phi / M + (Wa - Wr)\,\Delta To + 2\pi\,\Delta W/_{Wa}$$

where;

h = $|Error|_{max} \times To$
Wa = $Wo + \Delta W$ (actual source frequency)
M = multiplying factor
Wr = standard reference frequency
$\Delta\Phi$ = error associated with the measurement of phase
ΔTo = error associated with the measurement of time

TABLE VIII.1

frequency multiplier and heterodyne scheme on the uncertainty factor can be seen in the equations.

Using these formulas given in the table, and applying them to the specific system shown in Figure 20, it is apparent that,

$$To = \frac{2\pi}{Wb} = \frac{2\pi}{M(Wa-Wr)}$$

and that,

ΔTo = resolution of the frequency counter = $1/fc$, where f_c = counting rate of the counter

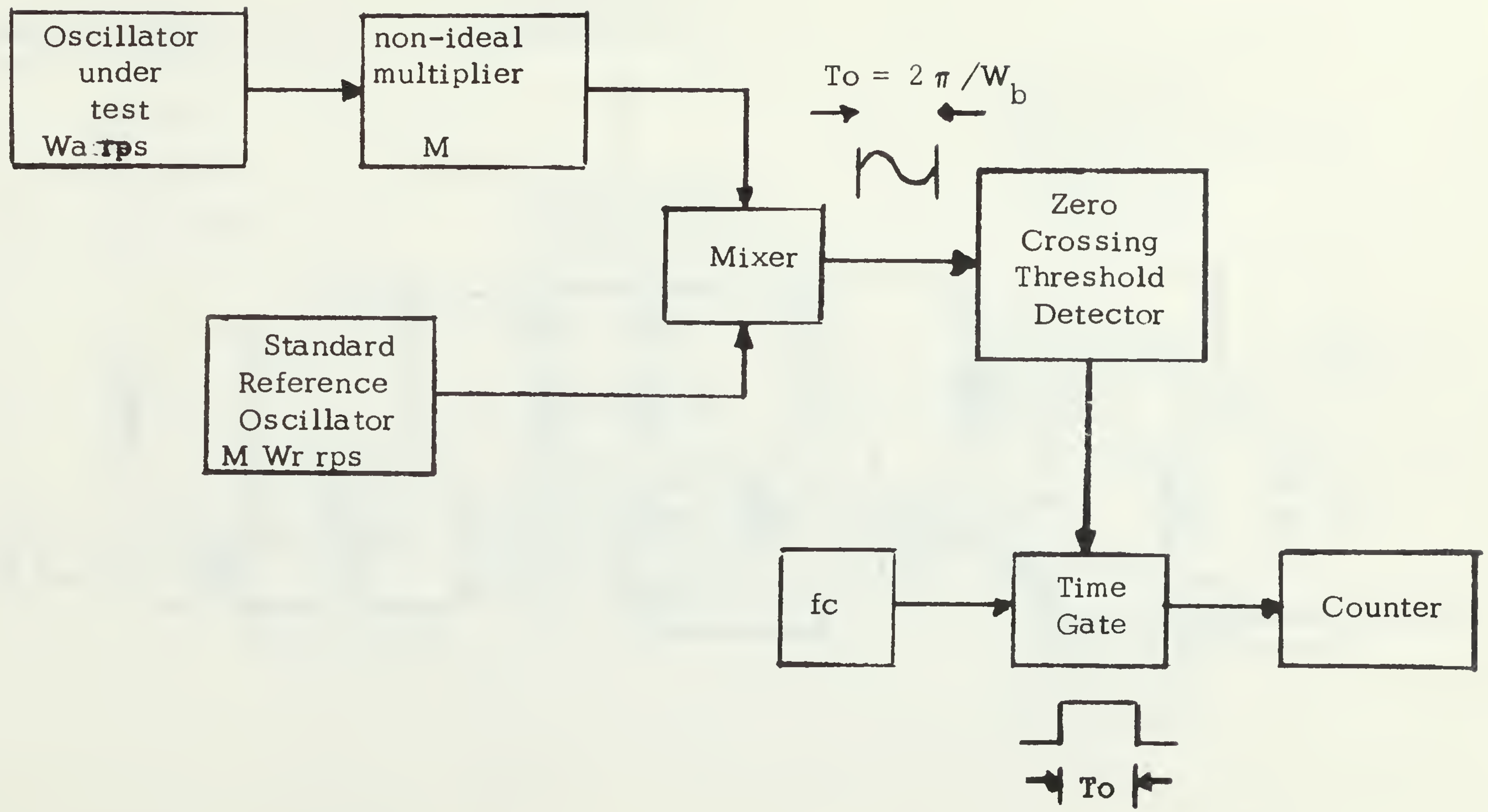
Using these values in the equation for the uncertainty for the Heterodyne Frequency Measuring System with a non-ideal multiplier, yields a maximum absolute error in radian frequency of

$$|E|\max = \frac{\Delta\Phi}{MTo} + \frac{2\pi\Delta To}{MTo^2} + \frac{2\pi\Delta W}{ToWa}$$

The first term of the error is due to error in measuring the phase caused by threshold detection. The second term reflects the error due to the plus or minus one count accuracy of the time base. The third term is error introduced by the multiplier. To be noted is the fact that the error introduced by the multiplier is a product of the multiplication factor, M, the degree of detuning of the multiplier from the source frequency, ΔW, and the chosen beat frequency, since,

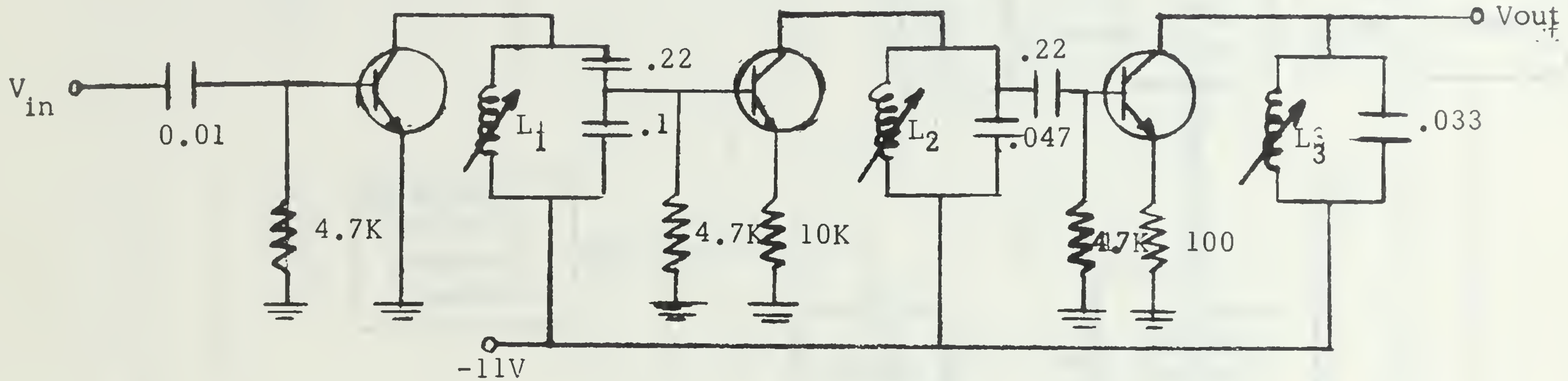
$$\frac{2\pi\Delta W}{To\,Wa} = \frac{M\Delta W\,Wb}{Wa}$$

A frequency multiplier, Class C amplifiers used as harmonic generators, was designed and built as shown in Figure 21. It was to be used in the proposed system shown in block diagram form in Figure 22.



Frequency Measurement System

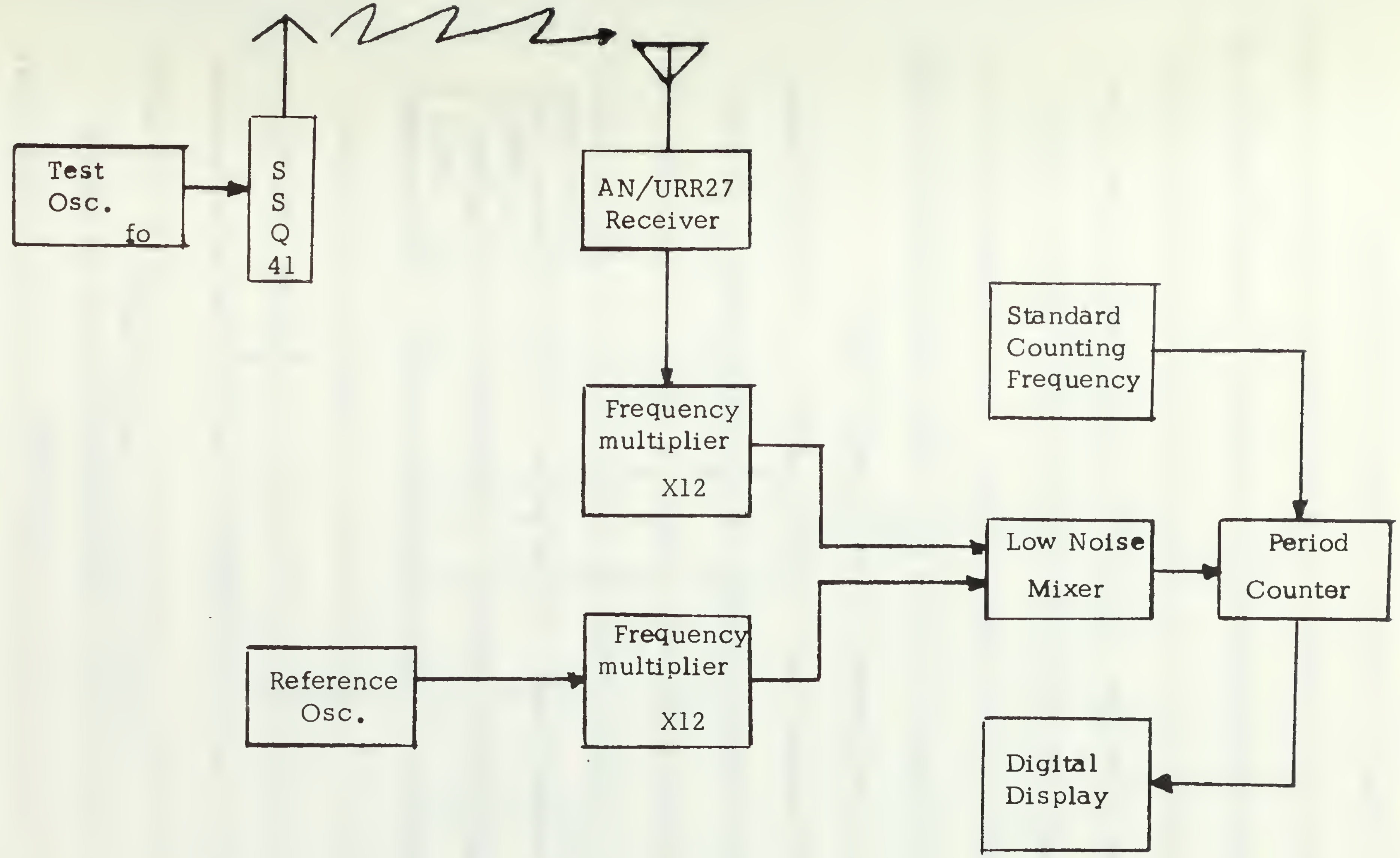
Figure 20



L_1 1.66 - 2.2 mh
L_2 495-760uh
L_3 138-238uh
All capacitors in uF
All transistors 2N329A

Circuit for Frequency Multiplier

Figure 21



Proposed Measurement System

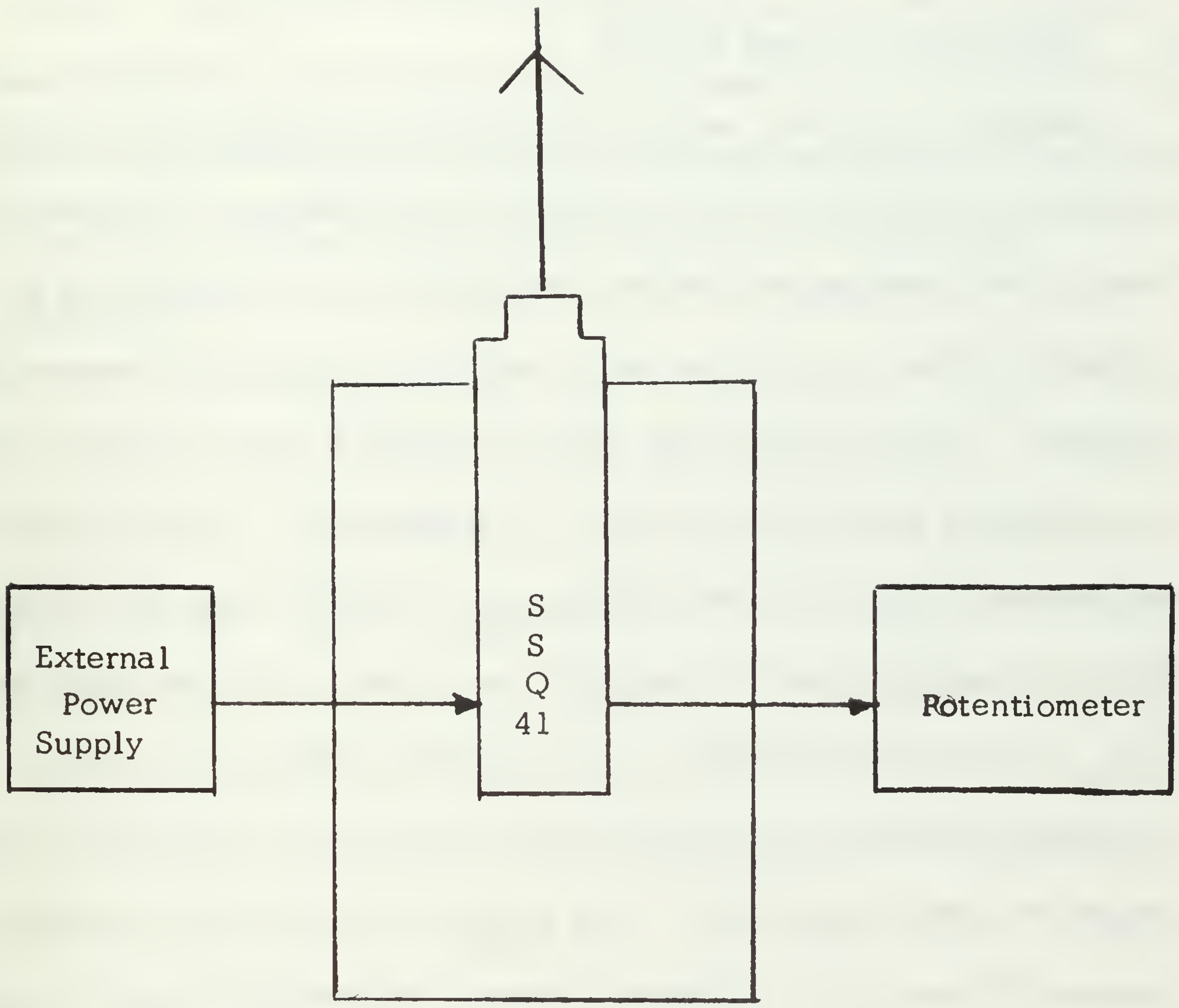
Figure 22

IX. INTERNAL SONOBUOY TEMPERATURE

Before an estimate of power requirements can be made, it is necessary to determine the temperature inside the sonobuoy, under the influence of different water temperatures while in operation. The specifications for the SSQ-41 sonobuoy require operation in a temperature environment over the approximate range from $-2^{\circ}C$ to $35^{\circ}C$. Before entry into the water, it would be stabilized between the limits of $-20^{\circ}C$ and $55^{\circ}C$. Normal laboratory conditions are considered to be : air temperature of $25^{\circ}C \pm 10^{\circ}C$, water temperature of $15^{\circ}C \pm 5^{\circ}C$. These specifications were used in evaluating the requirements for the proposed system.

An SSQ-41 sonobuoy was modified to determine its internal temperature under test conditions. Figure 23 is a block diagram of the test setup. Two thermocouples were mounted on opposite sides of the circuit boards in the sonobuoy to determine if there was a difference in temperature in the sonobuoy itself. For the purpose of this discussion, one side will be called the H_t side and the other side the L_t side. The modified sonobuoy was stabilized at room temperature, $23^{\circ}C$, and then immersed in water. The transmitter was activated, and the internal temperature monitered with a Leeds and Northrup millivolt potentiometer.

The results summarized in TABLE IX.1 indicate that the temperature at H_t was higher than at L_t by about $2-2.5^{\circ}C$. The test also verified the fact that the internal sonobuoy temperature will assume the ambient temperature of its surroundings (slightly higher on side H_t) within a very short time interval.



Block Diagram of Internal Sonobuoy
Temperature Test

Figure 23

time min.	H_t °C	L_t °C	time min.	H_t °C	L_t °C
	T(air) 23°C, T(water) 22°C			T(air) 23°C, T(water) 4°C	
0	23	23	0	23	23
5	24	23	5	13	12
10	25	23.3	10	10	7.5
15	25	23.3	15	7	5.5
20	25	23.3	20	7	5.5

TABLE IX.1 DATA SUMMARY
Sonobuoy Temperature Test

A. EVALUATION OF TEST RESULTS

The amount of power required to control the temperature of a crystal oscillator in an oven is directly related to the difference in temperature between the operating and ambient temperatures. The stability of the proposed system can of course be increased by reducing the temperature variation. The placement of the crystal oscillator in the sonobuoy would be affected by the fact that there is 2°C differential. If an oven were to be used with minimum power consumption, it would be operated slightly below the highest expected temperature encounter. The heat supplied at H_t would effectively reduce the temperature difference when the environment temperature was below the operating oven temperature, and reduce the power requirement. This would mean operating temperature between 0°C and 37°C. However, average temperatures should be within the 5°C to 25°C range.

Just as important as the operating temperature, is the rate at which the sonobuoy interior temperature stabilizes. Sonobuoys launched from internal storage in present aircraft, are stabilized near 25°C, the temperature of the interior of the aircraft. Those launched from newer

aircraft will be stored externally, and consequently will be stabilized at the air temperature at altitude. This could be anywhere from -20°C at 20,000 feet to 30°C at 200 feet. The test showed that the sonobuoy will be at or near the water temperature within approximately 15 minutes after entry. There was no appreciable difference in this figure when the water temperature was changed and the pre-entry temperature was held constant. Including the drop time, estimated at between 4-5 minutes from 20,000 feet, where gradual heating would begin, it could be reasonably assumed that the sonobuoy will be at sea temperature in less than 20 minutes after drop regardless of the pre-entry stabilization temperature.

X. DETERMINING THE INITIAL PHASE-RANGE RELATIONSHIP

Determining the phase of the range signal at a known range, in order to establish the phase-range relationship, is an important aspect of the proposed system. System accuracy can be no better than the accuracy of the initial determination. The problem of determining the initial relationship is complicated both by design and operational considerations.

There are two possible times at which the phase-range relationship can be determined, before and after drop from the aircraft. Determining the phase of the range signal before dropping the sonobuoy from the aircraft has several design problems. The most difficult problem is due to the external storage of sonobuoys in the newer ASW aircraft. If the phase-range relationship is to be determined at this time, the transmitter must be activated, and the range signal must be stabilized while in flight. This would mean either activating the entire sonobuoy system before take-off, or linking the sonobuoy to the aircraft by an umbilical cord to turn it on at the proper time. Activating the sonobuoy before take-off would require an additional power supply which may have to operate for up to 12-16 hours. Also, stabilizing the crystal with an oven during a flight at 20,000 feet would require considerable power. Sonobuoys not used in a given flight would have to be recharged before the next, increasing supply problems. The use of an umbilical cord connection to supply power would not be compatible with older ASW aircraft, and would therefore require two sonobuoy designs.

The alternative approach, to determine the phase-range relationship after drop, would be compatible with both new and old ASW aircraft. It may not be as accurate as the before drop determination, but it has far fewer design and operational problems. This method would involve a modified on-top procedure to make the initial determination. Power could be supplied by the modified silver chloride-magnesium battery which is presently contained in the sonobuoys. As shown in section 9, the sonobuoy internal temperature rapidly stabilizes to the sea temperature, so the additional power required would be far less than in stabilizing the crystal at altitude.

XI. SUMMARY

The conclusion of this investigation is that the proposed system is feasible. It is not intended that any aspects of the proposed system, as presented here, be considered as final designs. Choices were made, and offered as suggestions to solving some of the major areas of difficulty in the ranging system.

The basic concept of the system and its dependence on frequency stability have been discussed in detail. Methods of providing the range signal have been considered, and the decision to provide another oscillator for this purpose was justified in Sections VI and VII. Some aspects of measuring the phase of the received range signal were discussed. A measurement system utilizing a heterodyne scheme and frequency multipliers was proposed. Equations were given to determine the maximum error that could be expected in this type of measurement system. The problem of determining the initial phase-range relationship was treated. Two possible solutions were offered, and a preference was indicated with justifying reasons.

There are many areas in which further study must be made before a hardware implementation can be made. The most important area is in providing the necessary stability in the crystal oscillators. The possibility of combining temperature control and temperature compensation has been introduced. It should be investigated thoroughly because of its suitability in the proposed system. No matter what degree of stability is obtained, the error introduced must be removed. Crystal oscillators

must be obtained whose drift can be programmed in the on-board processing equipment to remove the accumulated error. Less stable, and therefore less expensive, oscillators can be used in the sonobuoys if the error introduced can be accurately removed in the on-board processing equipment. Because of fewer cost restrictions on the on-board measuring equipment, fewer design problems should be encountered. State-of-the-art measuring systems are commercially available which could be assembled for prototype tests.

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13. ABSTRACT

The ability to locate and determine the position of an ASW sonobuoy is an essential part of airborne anti-submarine operations. Present methods restrict the parent aircraft's operational capability and yield only marginal data. State-of-the-art frequency control makes it possible to range sonobuoys accurately with radio signals. Sonobuoy position can then be determined by combining this range data with other available information. A system is proposed to both free the parent aircraft from present restrictions and to increase the accuracy of the position information.

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Sonobuoy Ranging						
Radio Ranging						
ASW sonobuoy						
frequency control						
Anti-Submarine Operations						